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COMPUTER MODELING OF DIODE CIRCUITS AND ITS APPLICATIONS

Dr. Zeev I. Bogan
and
Dr. James B. Y. Tsui

Passive ECM Branch
Electronic Warfare Division

March 1978

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This technical report presents a computer model for calculation of multiple diode circuits. The model solves iteratively a system of nonlinear equations in the time domain and obtains frequency domain information by means of a Fourier series expansion. Applications for this model include prediction of one and two tone intermodulation performance for single-ended, balanced and double balanced mixers, calculation of the multiple-signal capture range of back-to-back diode limiters, and prediction of the performance of a frequency

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20. Abstract (Continued)

doubling front-end for detection and identification of Pseudo-Noise BPSK modulated signals. Experimental data was collected for some diode circuits. This data agreed qualitatively with the calculated results.

FOREWORD

This report was written by Drs. Zeev Bogan and James Tsui. Dr. Bogan was a National Research Council Resident Research Associate at the Electronic Warfare Division (WR), Air Force Avionics Laboratory (AFAL) during the period of June 1976 to November 1977. During this period, Dr. James Tsui, acted as his scientific advisor. The work was accomplished under Project Number 7633, Task Number 763311, "Real Time Threat Warning, Identification, and Location", Work Unit 76331115 "Receiver Concepts, Analysis, and Evaluation." The authors would like to thank the National Research Council for providing support to this research. Special thanks to Dr. Charles H. Krueger, Jr. and Mr. W. T. Brumfield for their valuable advice, encouragement, and interest in this research effort.

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SECTION I
INTRODUCTION

Some of the key elements in superheterodyne receivers, such as mixers and limiters, include semiconductor diodes as their basic devices. The nonlinear characteristics of these diodes strongly impact receiver performance. For example, insertion loss in a mixer will affect sensitivity while harmonic intermodulation products generated in the mixer will affect the dynamic range of the receiver; a limiter response to multiple signals will determine the multiple signal handling capability of the receiver. For proper receiver design, it is essential to predict the performance of such nonlinear elements under varying conditions. At the present stage, the nonlinear performance of mixers and limiters, such as intermodulation distortion and multiple signal handling, are determined experimentally. The "spur table" furnished by mixer manufacturers is one example. This table provides information at the various harmonic frequencies for an "optimal" local oscillator (LO) drive level. However, the use of this spur table is quite limited because variations in the LO drive level will affect the output level of the intermodulation (IMD) products. An ideal solution to this problem would be to theoretically calculate the output levels of the IMD products as a function of the LO drive level.

In this report, a mathematical model is presented by means of which the nonlinear responses of various diode circuits can be calculated. A single diode circuit with multiple input sources was simulated to demonstrate the capabilities of the model (Section II). The solution to the circuit is obtained first in the time domain using iterative methods. The time domain solution is then Fourier analyzed to extract the frequency components which are of interest to us. For this single diode circuit, single and two-tone intermodulation distortion levels were calculated using this model. A single ended mixer was constructed to verify the calculated results.

In the course of this investigation, it was found that some harmonic products which adversely affect superheterodyne reception might in

some applications become an asset. Such is the case, for example, in a frequency doubling receiver for detection and identification of pseudo-noise biphase-shift-key (PN-BPSK) modulated signals (Appendix A). Another application where harmonic intermodulation products may be proven useful, is the detection of the presence of a nonlinear device within a given volume. The volume is irradiated with a known signal and a specified harmonic product generated by the nonlinear device is detected, if such a device is present within that volume.

The single diode circuit model was extended to account for multiple diodes. Using the multiple diode circuit general model, presented in Section III-1, we can simulate a variety of diode circuits such as limiters (Section III-2), balanced and double balanced mixers (Sections III-3 and III-4 respectively). Results of these simulations along with experimental data are presented in Section IV.

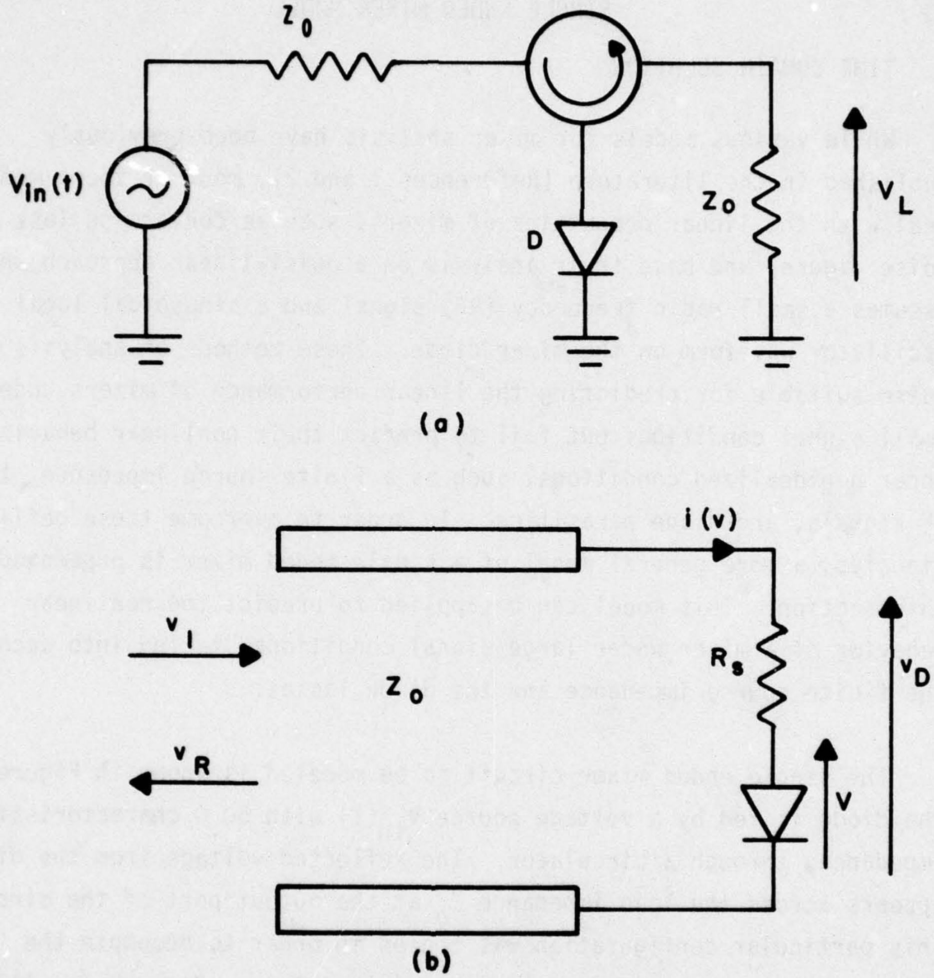
SECTION II

SINGLE ENDED MIXER MODEL

1. TIME DOMAIN SOLUTION

While various models for mixer analysis have been previously published in the literature (References 1 and 2), most of these models deal with the linear properties of mixers, such as conversion loss and noise figure, and base their analysis on a quasi-linear approach which assumes a small radio frequency (RF) signal and a sinusoidal local oscillator waveform on the mixer diode. These methods of analysis are quite suitable for predicting the linear performance of mixers under small signal conditions but fail to predict their nonlinear behavior under nonidealized conditions, such as a finite source impedance, large RF signals, and diode parasitics. In order to overcome these deficiencies, a more general model of a single ended mixer is presented in this section. This model can be applied to predict the nonlinear behavior of a mixer under large signal conditions, taking into account the finite source impedance and the diode losses.

The single ended mixer circuit to be modeled is shown in Figure 1a. The diode is fed by a voltage source $V_{in}(t)$ with 50 Ω characteristic impedance, through a circulator. The reflected voltage from the diode appears across the load impedance Z_o at the output port of the circulator. This particular configuration was chosen in order to decouple the output from the input and ease the measurement procedure which will be later discussed. It has to be noted that this model does not include reactive elements which ought to be taken into account if proper representation of the diode and package parasitics is desired. Neglecting reactive elements in the model will obviously introduce discrepancies between the measured and calculated results. However, this model simplifies the numerical calculations by avoiding the solution of nonlinear differential equations which may include very large time constants to account for the d.c. blocking capacitors and RF chokes.



$$i(v) = I_s\,(e^{\alpha v} - 1)$$

$$v_D = v_I + v_R$$

$$i = (v_I - v_R)/Z_o$$

$$v_I = V_{in}(t)/2\ ; \qquad v_L = v_R$$

Figure 1. Single Ended Mixer

The diode is modeled as a nonlinear conductance in series with a constant resistance (R_s). The current-voltage (I-V) characteristic of the diode is given by:

$$i = I_s \left[e^{\alpha(v_D - iR_s)} - 1\right] = I_s (e^{\alpha v} - 1) \tag{1}$$

where i is the current through the diode, I_s is the reverse saturation current, v_D is the voltage on its terminals, v is the voltage on the diode junction and $\alpha = \frac{q}{nKT}$ where q is the electronic charge, K is the Boltzmann constant and n is the quality factor of the junction ($1 \leq n \leq 2$) and T is the temperature in °K. The voltage on the diode $v_D(t)$ and the current through it i (t) are calculated from the boundary conditions on the diode plane:

$$v_D(t) = v_I + v_R \tag{2}$$

$$i(t) = (v_I - v_R)/Z_o \tag{3}$$

v_I and v_R are the incident and reflected voltages respectively (Figure 1b). From the matched conditions at the input port of the circulator,

$$V_I = V_{in}(t)/2 \tag{4}$$

The relationship between the voltage on the diode v_D and the voltage on the junction v, is given by:

$$v_D = v + iR_s \tag{5}$$

and the current-voltage relationship of the junction itself is given by Equation 1.

From Equations 1 through 5 the following transcendental equation for the voltage on the diode junction is derived:

$$F(v) = v + (Z_o + R_s)\, I_s (e^{\alpha v} - 1) - V_{in} = 0 \tag{6}$$

The diode parameters I_s, R_s and α are obtained for dc measurements on the diode, and Z_o is given.

The input voltage $V_{in}(t)$ is generally given as a sum of two sinusoidal waveforms at the LO and RF frequencies*:

$$V_{in}(t) = V_{LO}\sin\omega_{LO}\ t + V_{RF}\sin\omega_{RF}\ t \tag{7}$$

Equation (6) is now solved numerically at each point in time applying the Newton-Raphson method. Let v_n be the approximate solution of Equation 6 after n iterations, so that:

$$F(v_n) = v_n + (Z_o + R_s)\ I_s\ (e^{\alpha v_n} - 1) - V_{in} = \varepsilon \neq 0 \tag{8}$$

The solution at the next iteration will be given by:

$$v_{n+1} = v_n - F(v_n)/F'(v_n) \tag{9}$$

$$\text{where } F'(v_n) = \left.\frac{dF(v)}{dv}\right|_{v=v_n} = 1 + I_s\ \alpha\ (Z_o + R_s)\ e^{\alpha v_n} \tag{10}$$

The computation stops when the difference between the solutions at two consecutive iterations falls within a predetermined error range. After the junction voltage v(t) is obtained, the current through the diode i (t) is calculated and subsequently the voltages $v_D(t)$ and $v_R(t)$. The load voltage is given by:

$$v_L = v_R = v_D - v_I = v_D - V_{in}/2 \tag{11}$$

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*In case it is desired to calculate the two-tone third-order intermodulation (IMD) product, another term is added to $V_{in}(t)$:

$$V_{in}(t) = V_{LO}\ \sin\omega_{LO}\ t + V_{RF}\ (\sin\omega_{RF}\ t + \sin\omega'_{RF}\ t) \tag{7a}$$

where ω_{RF} and ω'_{RF} are the frequencies of the two tones.

Once the load voltage is known for an entire cycle, Fourier analysis is applied to obtain the output voltage at the various frequencies which are of interest to us.

2. FREQUENCY DOMAIN CALCULATIONS

The frequencies of the harmonic intermodulation products generated in a mixer are given by:

$$\omega_{mn} = |m\omega_{LO} + n\omega_{RF}| \tag{12}$$

where m and n are positive or negative integers. All (m,n) combinations other than (1, -1) which is the intermediate frequency (IF), are considered to be detrimental to heterodyne reception, but might be beneficial in other applications. The output amplitude at a particular IMD product (ω_{mn}) is obtained by Fourier analysis of $v_L(t)$:

$$v_L(\omega_{mn}) = \frac{2}{T_o} \int_0^{T_o} v_L(t)\, e^{-j\,\omega_{mn}\,t}\, dt \tag{13}$$

where $T_o = \frac{2\pi}{\omega o}$ is the period of v_L (t) and ω_o is the largest common divisor of ω_{LO} and ω_{RF}.

For numerical purposes it is convenient to choose the set (ω_{LO}, ω_{RF}) so as to minimize T_o in order to reduce computation time but at the same time care has to be taken in order to avoid overlapping of low order IMD products, meaning that $\omega_{n_1,m_1} \neq \omega_{n_2,m_2}$ for $m,n \leq 6$. The particular choice of the set (ω_{LO},ω_{RF}) for calculation purposes is irrelevant to the actual performance of the mixer, since the circuit model described in the previous section does not include frequency dependent elements.

For calculations of two-tone intermodulation levels the choice of the frequency set (ω_{LO}, ω_{RF}, ω'_{RF}) is guided by similar reasoning. The integration (Equation 13) is carried out numerically using the trapezoidal rule.

The computation of the output level at a given frequency ω_{mn} is now complete. From the given input voltage ($V_{in}(t)$) the voltage on the diode ($v(t)$) is calculated and subsequently the voltage on the load ($v_L(t)$) is obtained from circuit conditions. The desired frequency components of $v_L(t)$ are later calculated by a simple Fourier series expansion. Results of calculations using this model are presented in Section IV. These calculations are followed by experimental data taken on a similar circuit configuration.

In Section III, the single diode circuit model is expanded to multiple diode configurations.

SECTION III

MULTIPLE DIODE CIRCUIT SIMULATION

1. GENERAL MODEL

Consider the general circuit configuration shown in Figure 2. The circuit consists of a network of N interconnected diodes with M voltage inputs and a load impedance (Z_L). The diodes may or may not be identical and the parameters for each diode I_{sk}, R_{sk} and α_{sk} (k=1,2,....,N) are given. The voltage sources V_{in_j} (j=1,2,....M) are given by:

$$V_{in_j} = c_j V_{LO} \sin(\omega_{LO} t + \emptyset_j) + d_j V_{RF} \sin(\omega_{RF} t + \theta_j) \tag{14}$$

where c_j and d_j are constants.

We now expand the single diode circuit model developed in Section II to solve for the voltage on each diode $v_k(t)$ and eventually for the voltage on the load $v_L(t)$.

The homogeneous loop equation will have the form:

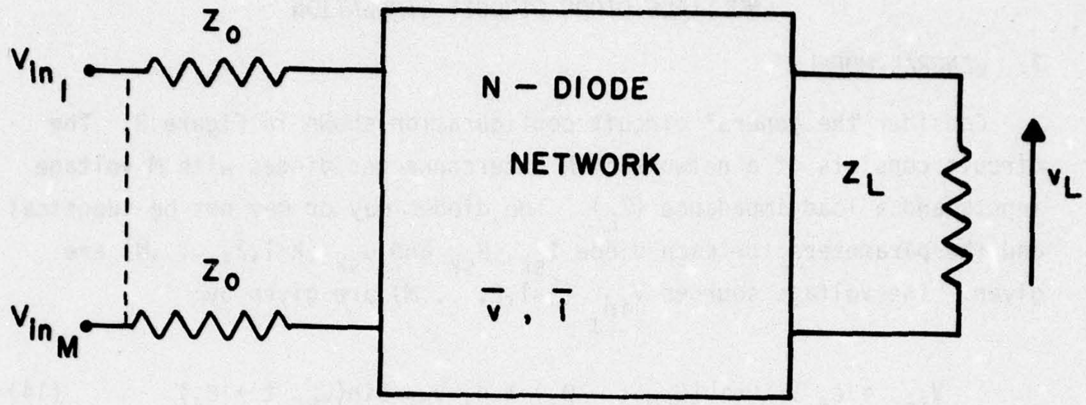
$$\overline{F}(\overline{v}) = A \overline{v} + Z \overline{i} + B \overline{V}_{in} = 0 \tag{15}$$

where $\overline{v}$ is the vector of the junction voltages, $\overline{i}$ is the vector of the diode currents, $\overline{V}_{in}$ is the input voltage vector, A and Z are N x N matrices, and B is an N x M matrix.

Similar to Equation 9 the approximate solution after n+1 iterations will be given by:

$$(\overline{v})_{n+1} = (\overline{v})_n - [J(\overline{v})_n]^{-1} [F(\overline{v})_n] \tag{16}$$

where $(\overline{v})_n$ is the solution at the previous iteration and $J(\overline{v})_n$ is the Jacobian of the system of Equation 15 evaluated at $\overline{v} = (\overline{v})_n$.



$$A\,\overline{v} + Z\,\overline{i} + B\,\overline{V}_{in} = 0$$

Figure 2. Multiple Diode Circuit Model

The elements of the Jacobian j_{ik}, are given by:

$$j_{ik} = \frac{\partial F_i(\overline{v})}{\partial v_k} = a_{ik} + a_{ik}\, i_k' \tag{17}$$

$$\text{where } i_k' = \frac{di_k}{dv_k} = \alpha_k\, I_{sk}\, e^{(\alpha_k\, v_k)} \tag{18}$$

In summary, once the matrices A, Z, B, and the input voltage vector $\overline{V}_{in}$ are known from circuit conditions, the solution for the voltages on the diodes $\overline{v}$ is straight-forward using Equation 16. As an example, the matrices for the single ended mixer case discussed in the previous section are given by:

$$A = 1\ ;\ B = 1\ ;\ Z = (R_s + Z_o); \tag{19}$$

$$J = 1 + (R_s + Z_o)\ \alpha\, I_s\, e^{\alpha\, v}$$

In the following sections the above matrices will be calculated for various circuits, namely, balanced and double balanced mixers and back-to-back diode limiters.

2. BACK-TO-BACK DIODE LIMITER

The multiple signal handling capability of a receiver is strongly affected by the performance of the limiter. The ideal input-output characteristic of a limiter is plotted in Figure 3a. Using the model developed in this section we can calculate the deviations from this ideal characteristic when two or more input signals are present at the limiter input.

The equivalent circuit of a back-to-back diode limiter is shown in Figure 3b. From loop analysis of this circuit we obtain the following system of equations:

$$F_1(v_1,v_2) = v_1 + (R_{s1} + Z_{eq})\, i_1 - Z_{eq}\, i_2 - \frac{Z_{eq}}{Z_o} V_{in} = 0 \qquad (20)$$

$$F_2(v_1,v_2) = v_1 + v_2 + R_{s1}\, i_1 + R_{s2}\, i_2 = 0 \qquad (21)$$

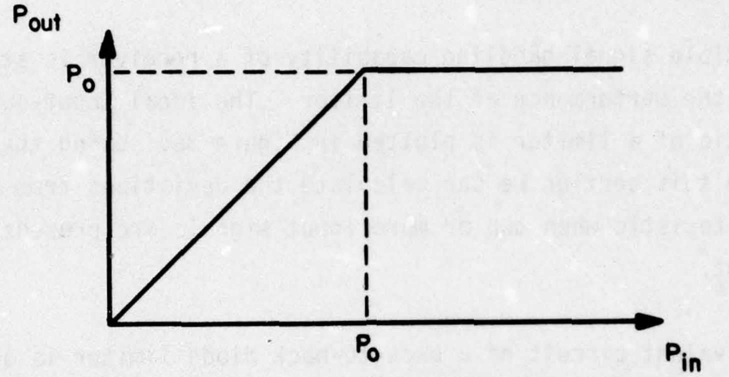
where $Z_{eq} = Z_o // Z_L$.

The circuit matrices for this case are given by:

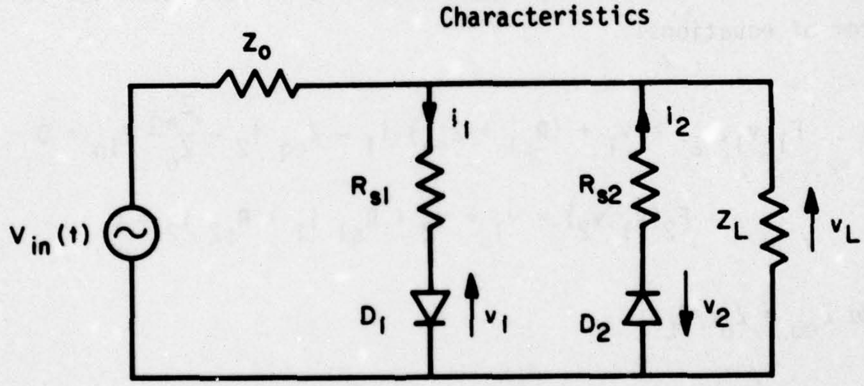
$$A = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} ; \; B = \begin{bmatrix} -Z_{eq}/Z_o \\ 0 \end{bmatrix} ; \; Z = \begin{bmatrix} R_{s1} + Z_{eq} & -Z_{eq} \\ R_{s1} & R_{s2} \end{bmatrix} \qquad (22)$$

The voltage on the load, v_L, is given by:

$$v_L = v_1 + i_1 R_{s1} \qquad (23)$$



(a) Ideal Characteristics



(b) Equivalent Circuit

Figure 3. Back-To-Back Diode Limiter

3. BALANCED MIXER

A simplified circuit of a balanced mixer using a 90° hybrid is shown in Figure 4a. From loop analysis of the equivalent circuit (Figure 4b) we obtain the following circuit matrices:

$$A = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; \qquad B = \frac{\sqrt{2}}{2}\begin{bmatrix} -1 & -e^{-j\pi/2} \\ e^{-j\pi/2} & 1 \end{bmatrix}$$

$$Z = \begin{bmatrix} Z_o+Z_L+R_{s1} & -Z_L \\ -Z_L & Z_o+Z_L+R_{s2} \end{bmatrix} \tag{24}$$

$$\overline{V}_{in} = \begin{bmatrix} V_{RF}\cos\omega_{RF}\, t \\ V_{LO}\cos\omega_{LO}\, t \end{bmatrix}$$

The voltage on the load is given by:

$$v_L = (i_1 - i_2)\, Z_L \tag{25}$$

Note that the input voltage vector V_{in} is chosen in such a manner as to enable rapid convergence of the solution at t=0. Rapid convergence at t=0 is assured when the diodes are back biased or at a very low forward conduction state.

For a balanced mixer using a 180° hybrid, the A and Z matrices are the same as in the 90° hybrid case. The B matrix and the input voltage vector $\overline{V}_{in}$ will be given in this case by:

$$B = \frac{\sqrt{2}}{2}\begin{bmatrix} -1 & -1 \\ -1 & -1 \end{bmatrix}; \quad \overline{V}_{in} = \begin{bmatrix} V_{LO}\sin\omega_{LO}\, t \\ V_{RF}\sin\omega_{RF}\, t \end{bmatrix} \tag{26}$$

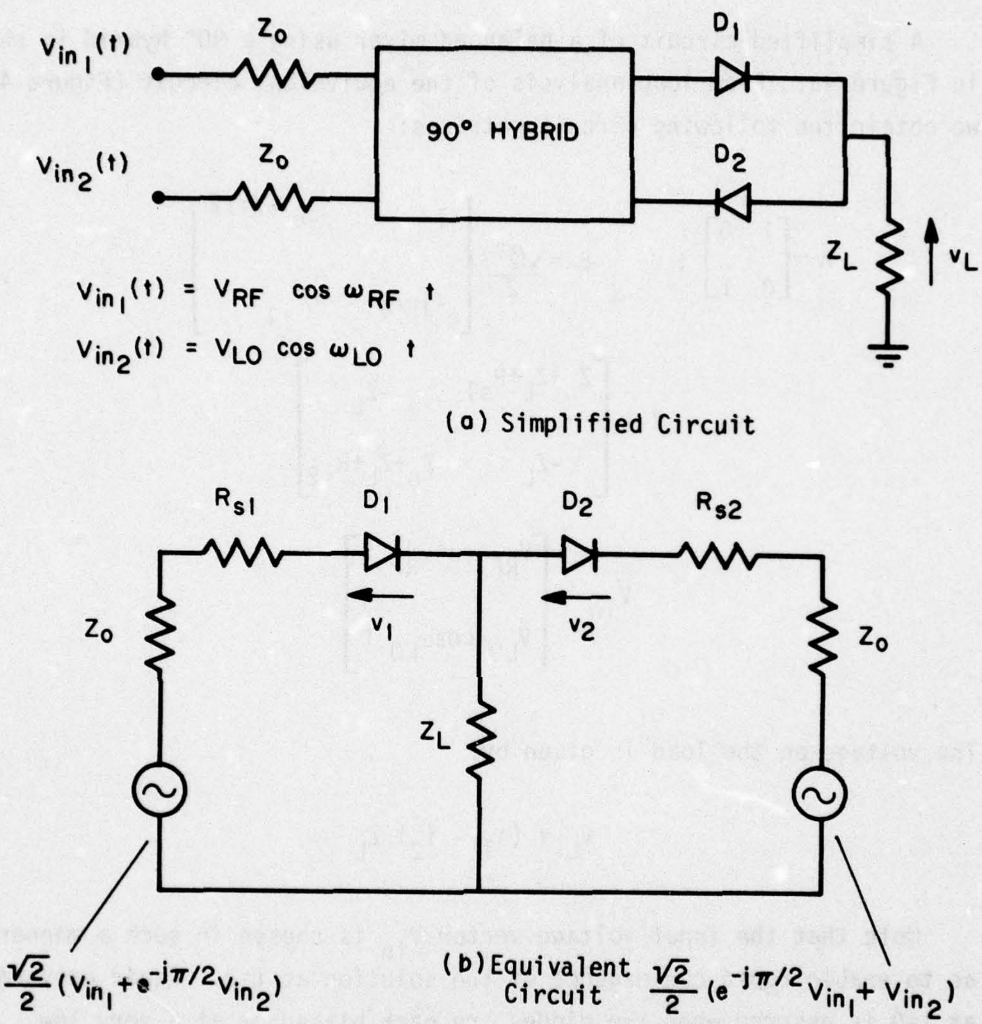


Figure 4. 90° Hybrid Balanced Mixer

4. DOUBLE BALANCED MIXER

The simplified circuit of a double balanced mixer is shown in Figure 5a. This mixer is analyzed using the equivalent circuit in Figure 5b. A and Z are in this case, 4 x 4 matrices and B is a 4 x 2 matrix.

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} ; \quad B = \begin{bmatrix} -1 & 0 \\ 0 & -1 \\ -\frac{1}{2} & -\frac{1}{2} \\ 0 & 0 \end{bmatrix}$$

$$Z = \begin{bmatrix} R_{s1}+\frac{1}{2}Z_o & R_{s2}+\frac{1}{2}Z_o & -\frac{1}{2}Z_o & -\frac{1}{2}Z_o \\ -\frac{1}{2}Z_o & R_{s2}+\frac{1}{2}Z_o & R_{s3}+\frac{1}{2}Z_o & -\frac{1}{2}Z_o \\ -(\frac{1}{2}Z_o+Z_L) & R_{s2}+Z_o+Z_L & -(\frac{1}{2}Z_o+Z_L) & Z_L \\ R_{s1} & R_{s2} & R_{s3} & R_{s4} \end{bmatrix} \tag{27}$$

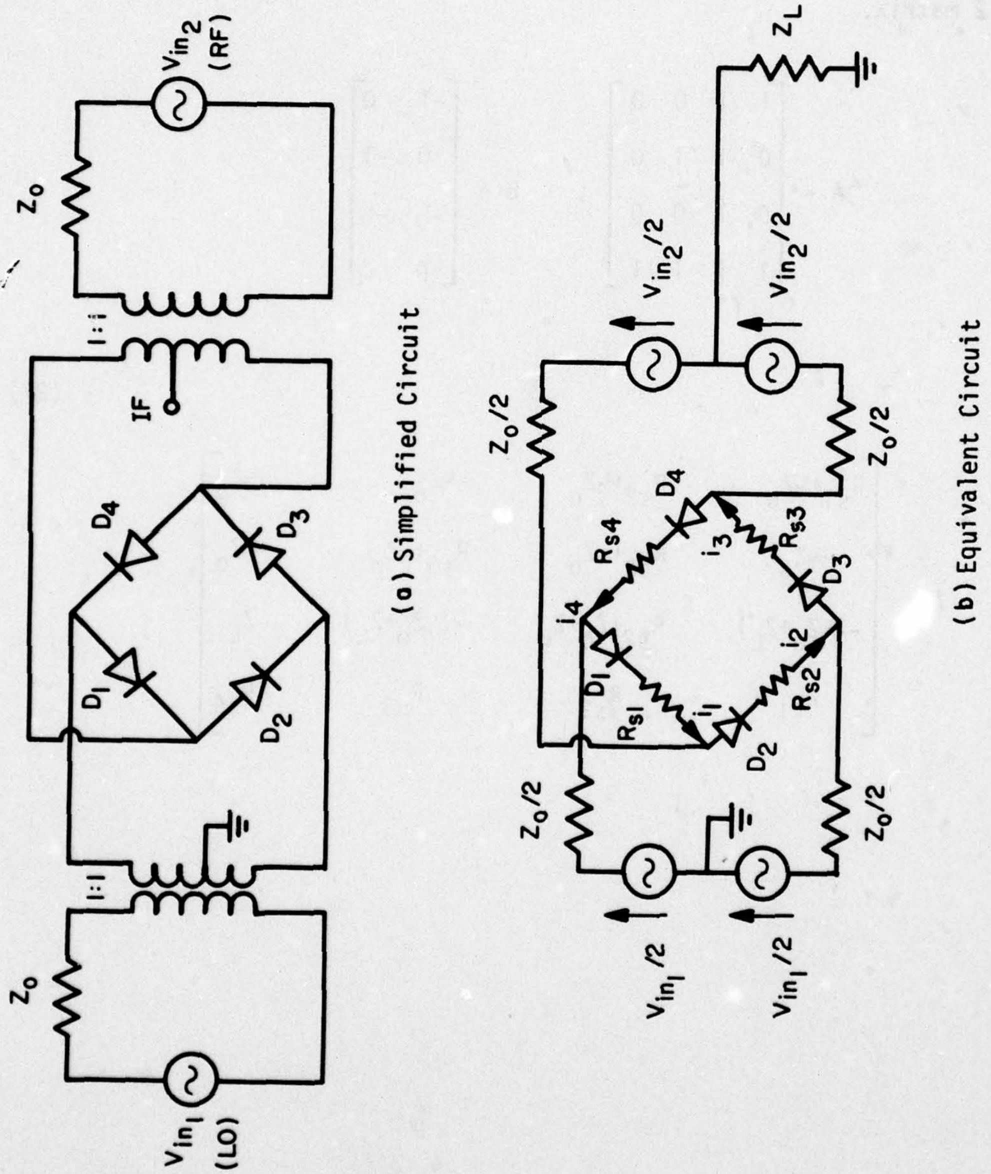


Figure 5. Double Balanced Mixer

SECTION IV

COMPUTER EXPERIMENTS ON DIODE CIRCUITS

1. CALCULATIONS AND MEASUREMENTS ON A SINGLE ENDED MIXER

Two specific applications for the single ended mixer model were investigated in particular. The first case is the detection of the presence of a nonlinear device within a given volume by irradiating this volume with a known signal and detecting a specified harmonic product of the transmitted signal.

This method is widely applied in commercial antishoplifting systems where a diode is attached to the protected merchandise and irradiated by a signal at f_o. A receiver at the entrance to the store detects the second harmonic at $2f_o$ generated by the diode and activates an alarm. A variation of this method can be applied when it is preferred to have the harmonic product generated by the nonlinear device in the same frequency range as the transmitted signal. For this purpose, two equal amplitude signals at f_1 and f_2 are transmitted so that

$$V_{in}(t) = V_o \ (\sin \omega_1 t + \sin \omega_2 t) \tag{28}$$

The product $|2f_1 - f_2|$ (or $|2f_2 - f_1|$) is then detected if a nonlinear device is present within the irradiated volume.

The model developed in Section II was applied to evaluate the efficacy of this method. The calculated and measured power output at various intermodulation products as a function of the power input (P_{in}) is shown in Figures 6 and 7 respectively.

The experimental results were taken on a homemade mixer constructed by mounting a detector diode in a shorted N-type connector without the benefit of any matching networks. The experimental setup used is shown in Figure 8. The static I-V characteristics of the diode were measured on a curve tracer and the diode parameters α, I_s, and R_s were matched to this curve and used in the computer simulation.

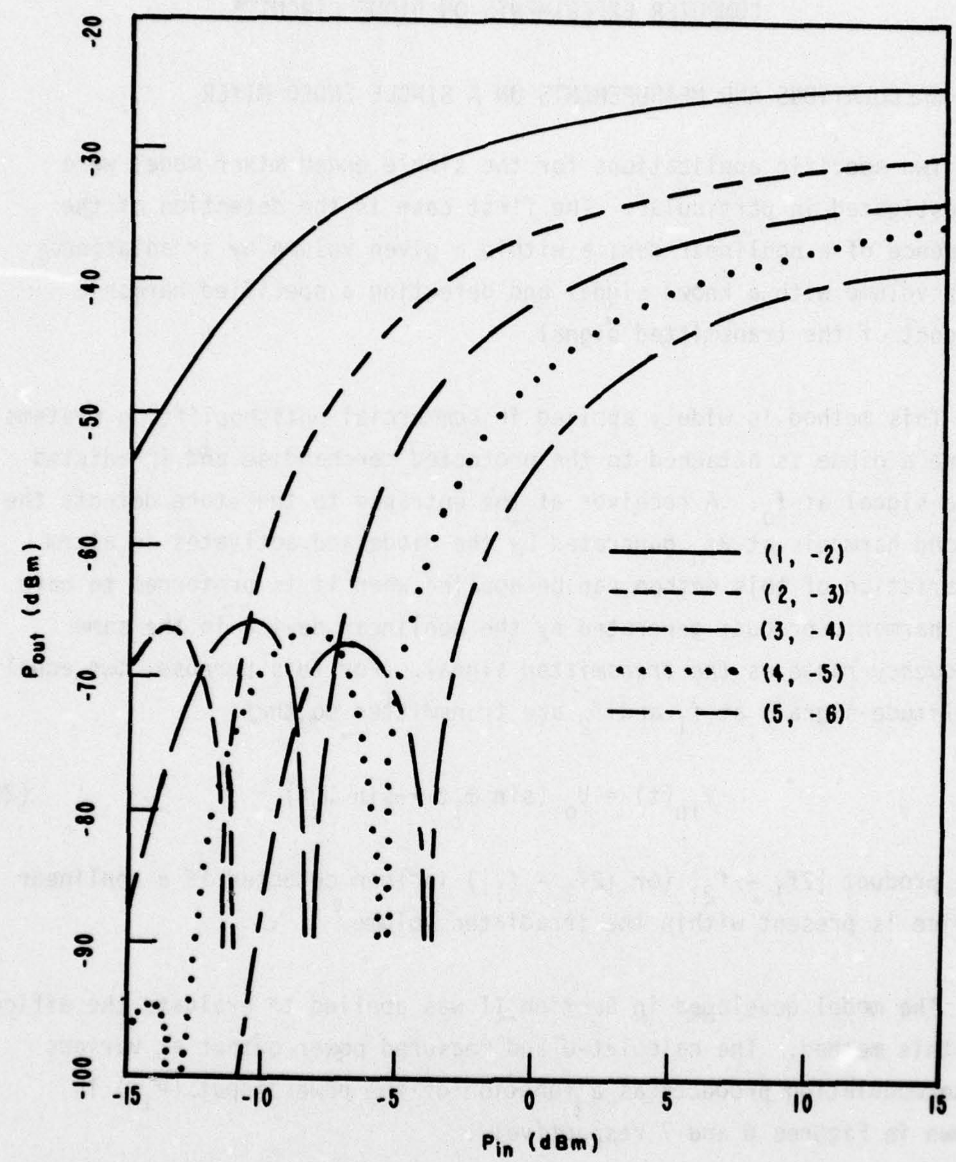


Figure 6. Calculated Power Output (P_{out}) of (m,n) IMD Products as a Function of the Power Input (P_{in}). (P_1=P_2=P_{in})

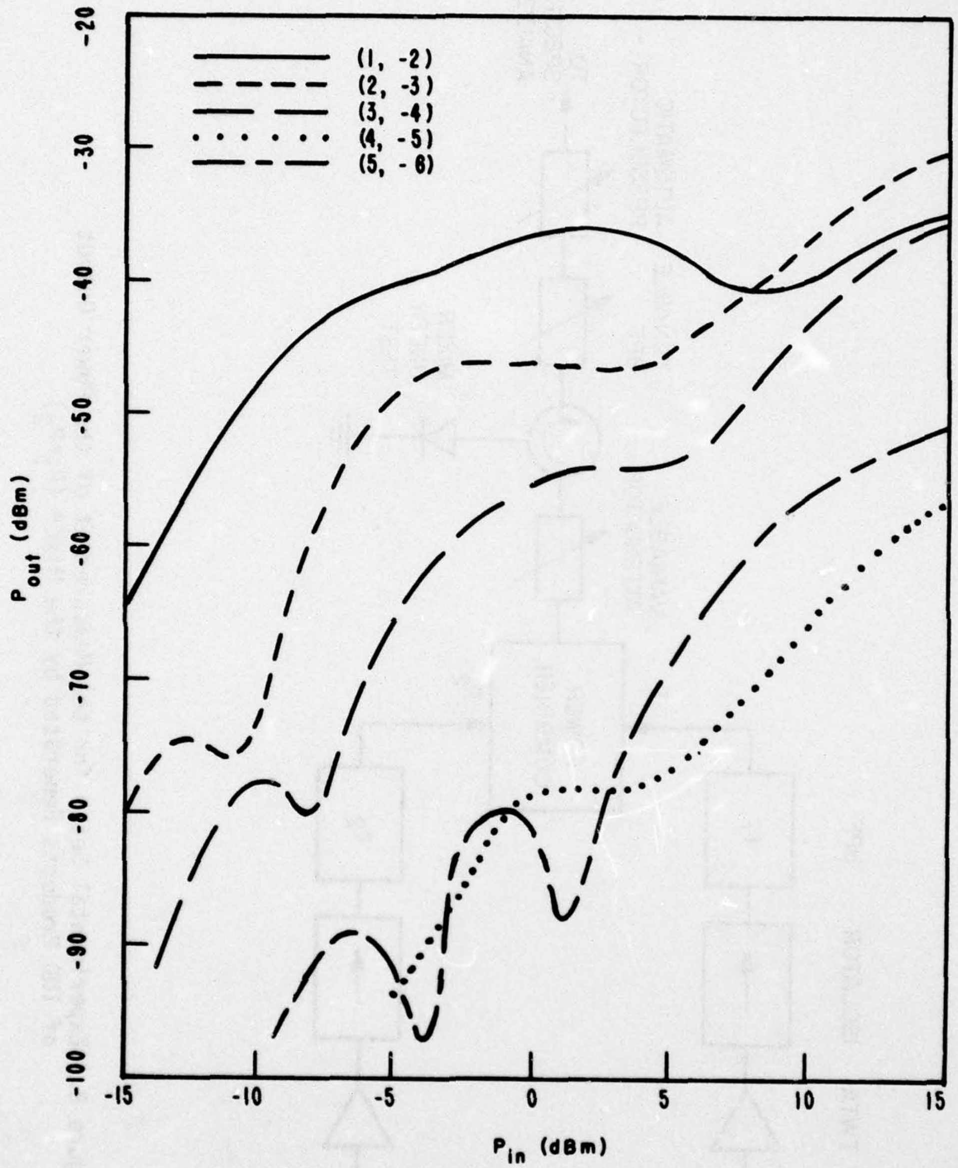


Figure 7. Measured Power Output (P_{out}) of (m,n) IMD Products as a Function of P_{in}. (P_1=P_2=P_{in})

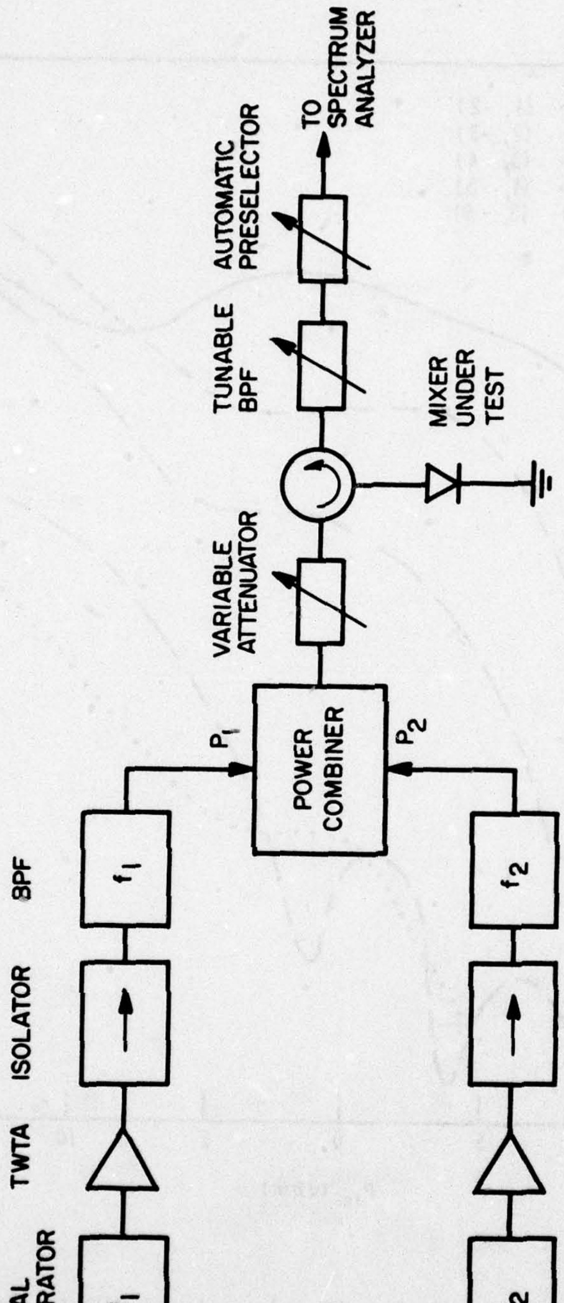


Figure 8. Experimental Setup for the Measurement of the Power Output of IMD Products Generated by the Mixer ($P_1=P_2$)

The results of this simulation (Figure 6) show that for some levels of input power, some of the IMD products completely disappear. A similar phenomenon was observed in the experimental data, as shown in Figure 7. Although in this case the output levels do not drop as drastically as in the simulated case, dips in the power output of the various IMD products were seen to occur for given input power levels. The numerical discrepancies between the calculated and measured results could be attributed to the fact that the computer model does not include frequency effects, while the experimental setup is frequency limited. In addition, the I-V diode characteristic is not strictly exponential as assumed in the computer model.

Another possible application for this model is to predict the level of the second harmonic generated in a diode in order to evaluate the feasibility of detection and identification of pseudo-noise BPSK modulated signals by a frequency doubling technique. The details of this investigation are presented in Appendix A.

The two-tone third-order intercept point in a mixer can be predicted as a function of the local oscillator drive level using the model presented here. For example, the intercept point for the single-ended mixer previously simulated was calculated for three values of LO drive level. The results, along with the RF to IF conversion loss at these LO levels, are shown in Table 1.

TABLE 1

TWO-TONE THIRD ORDER INTERCEPT POINT AND INSERTION LOSS AT VARIOUS LO DRIVE LEVELS. (SINGLE-ENDED MIXER)

P_{LO} (dBm)	THIRD ORDER INTERCEPT (dBm)	INSERTION LOSS (dB)
3	11.1	11.3
6	14.5	10.9
9	17.7	10.7

It is seen that in this range, an increase of 3 dB in the LO drive level will increase the intercept point by more than 3 dB while slightly improving the insertion loss of the mixer. Thus, by using this model, an LO power can be calculated which would be optimal for our purposes, be it maximum linearity, minimum conversion loss, suppression or enhancement of a particular IMD product, etc.

2. BACK-TO-BACK DIODE LIMITER

The performance of a back-to-back diode limiter with an input consisting of two signals at f_1 and f_2, was simulated using the formulation presented in Section III-2. The output power at f_1 (P_{out_1}) was calcuated as a function of the input power at f_1 (P_{in_1}) with the input power at f_2 (P_{in_2}) as a parameter. Results of this calculation are shown in Figure 9. The simulated diodes were considered lossless (R_s=0), but for one case where a spurious series resistance was added (R_s = 5Ω) in order to evaluate its effect on the performance of the limiter (dotted line).

As seen in Figure 9, the presence of a series resistance in the diode is detrimental to the limiting effect. The increase in current through the diodes due to increasing input power yields a higher voltage on the diode terminals, canceling the limiting effect of the junction itself.

Figure 9 also shows the effect of the presence of a second signal at the input of the limiter. The attenuation is linear with P_{in_1} for $P_{in_2} \geq P_{max}$, where P_{max} is the maximum output power. This is the "capture effect" of the limiter, where the stronger signal prevails and the weaker signal is further attenuated. This effect is clearly seen in Figure 10, where the output power of both signals is plotted.

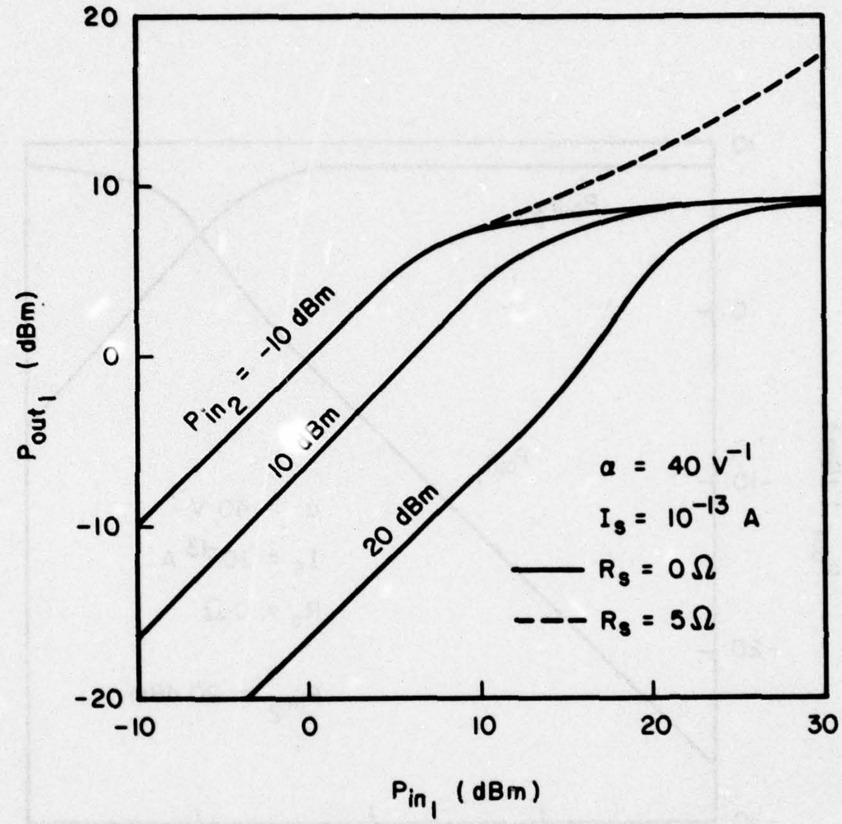


Figure 9. Simulation of a Limiter Fed by Two Signals at f_1 and f_2: Power Output (P_{out_1}) Vs. Power Input at f_1 (P_{in_1}) With the Power Input at f_2 (P_{in_2}) as a Parameter

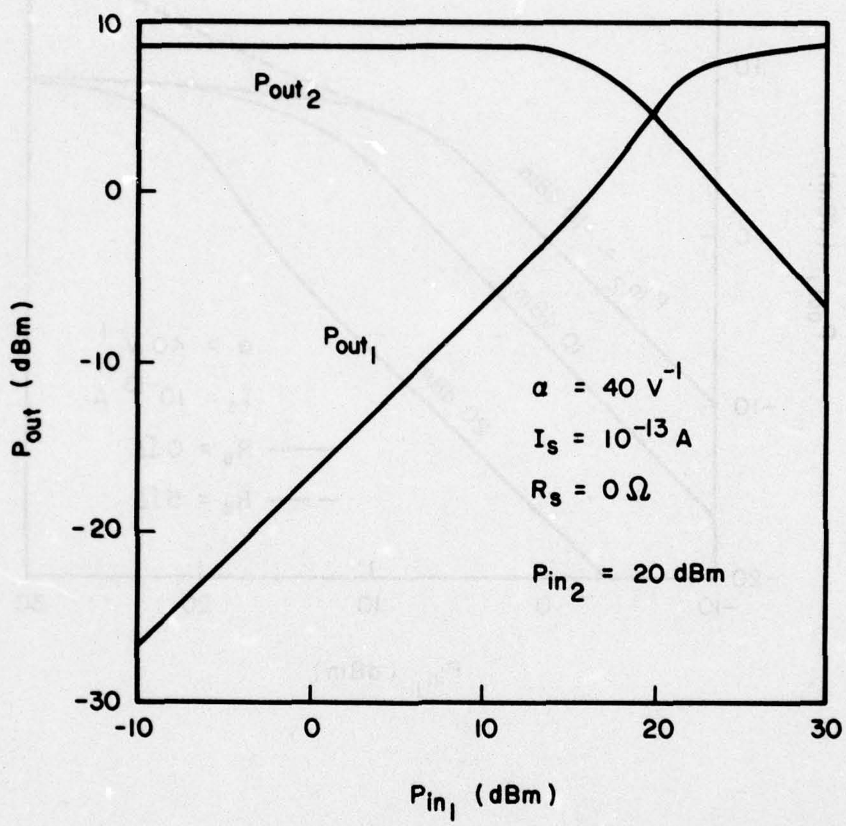


Figure 10. Simulation of a Limiter Fed by Two Signals at f_1 and f_2: P_{out} at f_1 and f_2 Vs. P_{in_1} P_{in_2} = const.

3. 90° HYBRID BALANCED MIXER

A simulation of a 90° hybrid balanced mixer with identical diodes was carried on using the equations in Section III-3. Two cases were investigated:

a. Insertion loss and two-tone third-order intercept as a function of the local oscillator power level (Figure 11).

b. IF and single-tone IMD output levels as a function of RF input power (Figure 12).

As in the single-ended mixer case, increasing the LO power level will greatly improve linearity (higher intercept point) while slightly reducing insertion loss (Figure 11). The IF and IMD plots (Figure 12) are similar to those supplied by mixer manufacturers but for the "dips" in the output levels of the 2 x 2 and 1 x 2 products, ($m \times n \equiv |mf_{LO} - nf_{RF}|$). These dips appear in this simulation at high input power levels generally not measured by the manufacturers. No physical explanation for this phenomenon has been found by the authors. Mathematically, the load voltages at these products, which are calculated from a Fourier series expansion, change sign at these input RF levels.

Additional examples of applications of the model are presented in Appendix B, along with program usage instructions and the program listing.

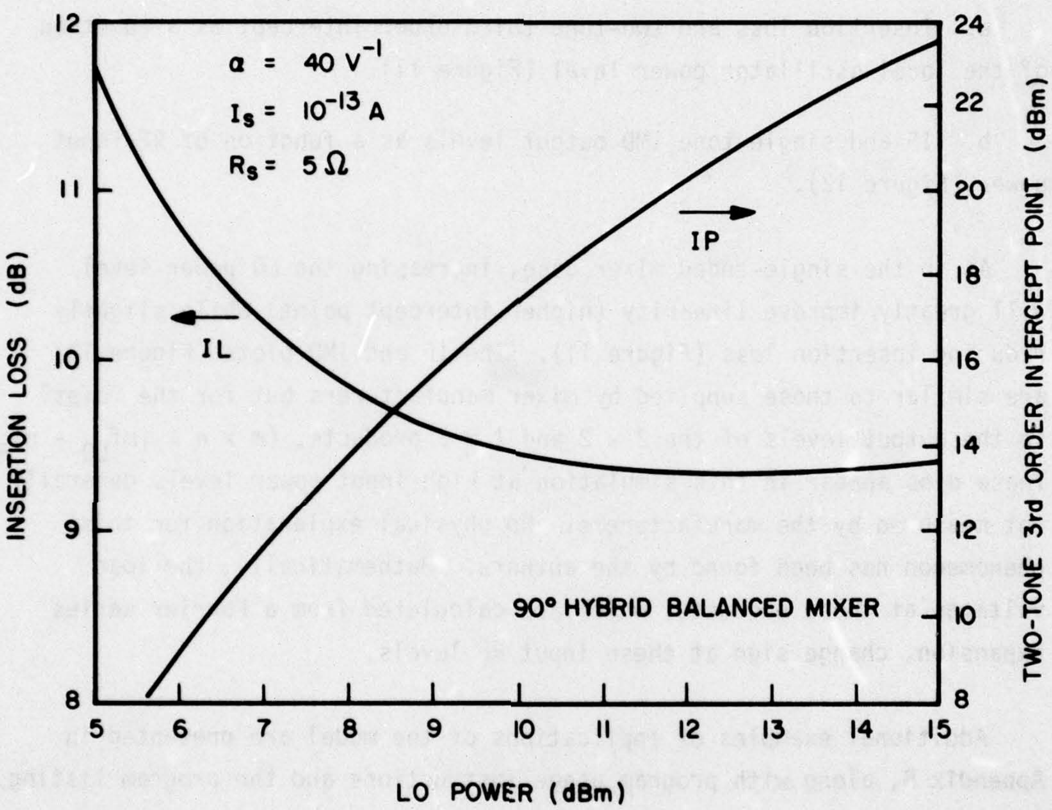


Figure 11. Calculated Insertion Loss and Two-Tone Third-Order IMD Intercept Point as a Function of the LO Power, for a 90° Hybrid Balanced Mixer

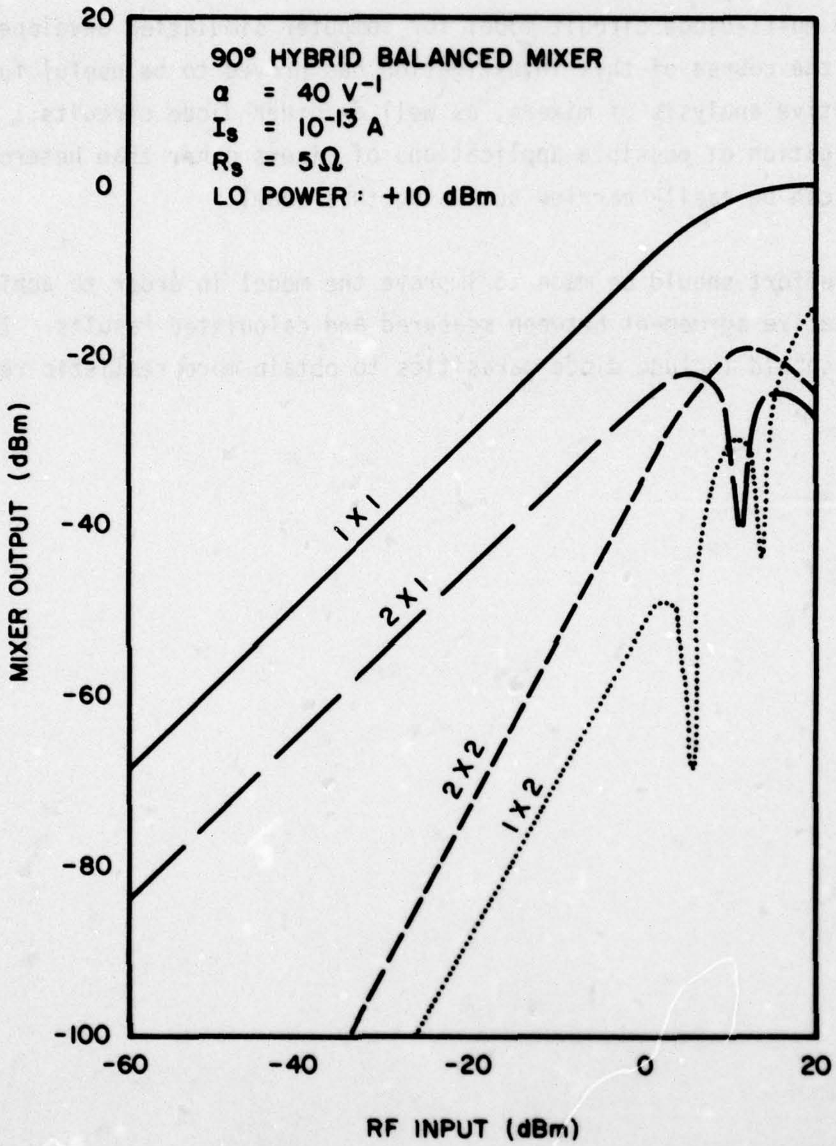


Figure 12. Calculated Single-Tone IMD Response for a 90° Hybrid Balanced Mixer

SECTION V

CONCLUSIONS

The multi-diode circuit model for computer simulation developed during the course of this investigation has proved to be useful for qualitative analysis of mixers, as well as other diode circuits. Investigation of possible applications of mixers other than heterodyne mixing can be easily carried out using this model.

An effort should be made to improve the model in order to achieve quantitative agreement between measured and calculated results. This effort should include diode parasitics to obtain more realistic results.

APPENDIX A

PSEUDO-NOISE BPSK SIGNAL DETECTION BY HETERODYNE MIXING

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Detection of the presence of Pseudo-Noise Bi-Phase Shift Keyed signals from uncooperative sources is extremely difficult due to their noise like and suppressed carrier characteristics.

A method which facilitates detection of such signals is presented. The method consists of squaring the incoming signal by means of a non-linear device in the presence of a pumping signal. The squaring process eliminates the bi-phase modulation, thus obtaining a CW signal at the second harmonic of the carrier frequency. By pumping the non-linear device with a local oscillator signal, significant enhancement of the second harmonic output is obtained, with a distinctive peak in output power at a given pump level. Moreover, this method makes it possible to down-convert the second harmonic signal to a lower frequency without considerable loss, facilitating the post-processing.

The described method was tested successfully both by computer simulation and laboratory experiments.

INTRODUCTION

The non-linear properties of a heterodyne mixer, which adversely affect reception by generation of spurious signals, might in some applications become an asset. Such is the case presented here in which the mixer non-linearities are investigated as a means to the detection of the presence of Pseudo-Noise-BPSK signals from uncooperative sources.

The time function of a pseudo-noise-bi-phase modulated signal is given by:

$$V(t) = V_c \cos\{\omega_c t + \phi(t)\} \qquad (1)$$

where ω_c is the carrier frequency and the phase $\phi(t)$ changes in a pseudo random fashion between 0 and π, controlled by a direct sequency modulator.

The power spectrum of such a signal which appears to be noise with a $(\sin x/x)^2$ distribution is shown in Fig 1(a).

This spectrum is obviously similar to that of a pulsed RF signal with a small duty cycle. An operator monitoring the spectrum and detecting a signal with such a power distribution on his display could not immediately decide if it is a PN or a pulse modulated signal. If time is no factor, however, a PN signal could be identified by its suppressed carrier characteristics, Fig 1(b).

An additional method for identification of a PN signal as such is suggested here. The method consists of obtaining a CW signal at the second harmonic of the carrier frequency by squaring the incoming signal in the presence of a pump (local oscillator). Applying this method, it is also possible to obtain a down-converted CW signal by heterodyne mixing of the pump frequency with the second harmonic of the carrier.

MATHEMATICAL FORMULATION

The squaring of the incoming signal is accomplished by means of a non-linear device, such as a semi-conductor diode. The output from such a device can be represented, for a small signal regime, as a power series of the form:

$$V_{out}(t) = \sum_{k=o}^{\infty} A_k V_{in}^{\ k}(t) \qquad (2)$$

Expanding the quadratic term with $V_{in}(t)$ as given in (1), we get:

$$A_2 V_{in}^{\ 2}(t) = A_2 V_c^{\ 2} \cos^2\{\omega_c t + \phi(t)\} =$$

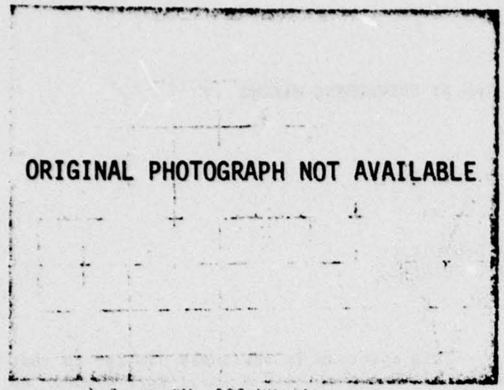
$$= \frac{A_2}{2} V_c^{\ 2} \{\cos\left[2\omega_c t + 2\phi(t)\right] + 1\}$$

but since $\phi(t)$ is either o or π, therefore

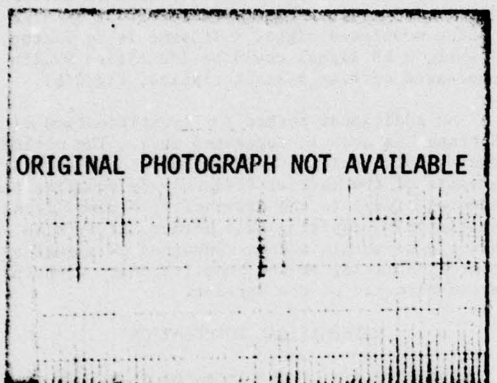
$$A_2 V_{in}^{\ 2}(t) = \frac{A_2}{2} V_c^{\ 2} \left[\cos 2\omega_c t + 1\right] \qquad (3)$$

Thus eliminating the phase modulation of the original signal and obtaining a CW signal at $2\omega_c$ with an amplitude of $A_2 V_c^{\ 2}/2$; if we take into account the fourth order term also, the amplitude at the second harmonic will be

$$\frac{A_2 V_c^{\ 2}}{2} \left(1 + \frac{A_4}{A_2} V_c^{\ 2}\right).$$



a) 3 KHz BW, 500 KHz/div



b) 1 KHz BW, 50 KHz/div

Fig 1: Power Spectrum of a PN-BPSK signal (10 dB/div). f_c = 2200MHz, 1 MHz clock, 127 bits sequence length.

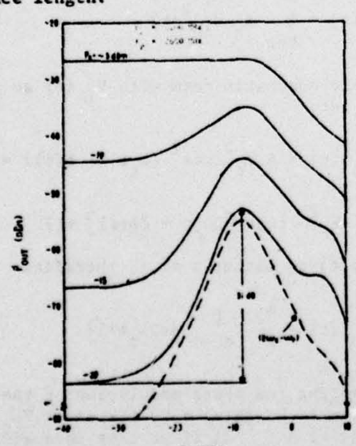


Fig 2: Calculated power output at $2\omega_c-\omega_p$ as a function of the pump power P_p, with the carrier power P_c as a parameter.

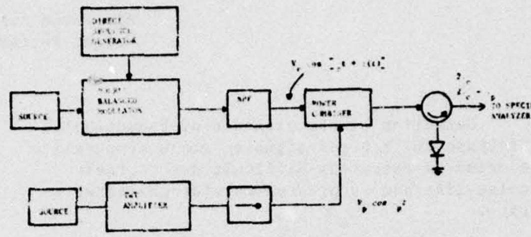


Fig 3: Experimental Set-Up

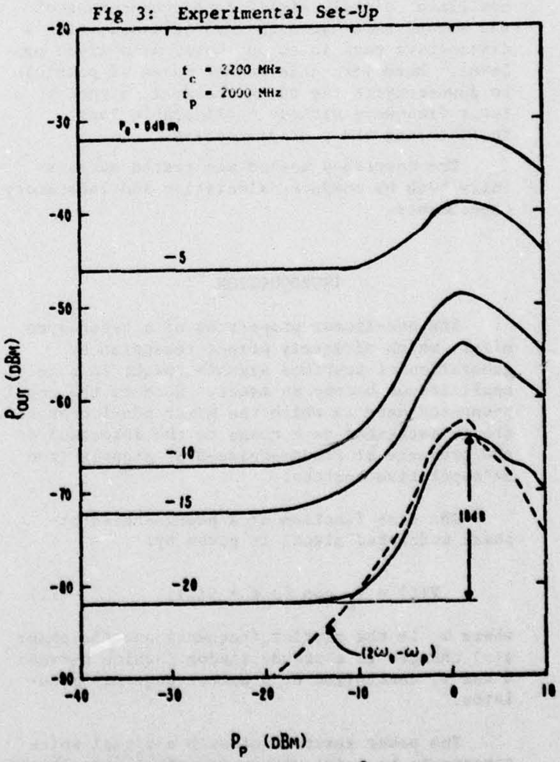


Fig 4: Measured power output at $2\omega_c-\omega_p$ as a function of the pump power P_p, with the carrier power P_c as a parameter.

This process is bound to be lossy due to its quadratic characteristic, especially at small signal levels, where this model applies. Some improvement can be obtained, however, by superimposing on the incoming signal a pump with an amplitude of V_p at a frequency of ω_p, so that the input voltage to the non-linear device will be now:

$$V_{in}(t) = V_c \cos[\omega_c t + \phi(t)] + V_p \cos \omega_p t \qquad (4)$$

Let us now calculate the second and fourth order terms in (2) and extract the second harmonic component:

$$A_2 V_{in}^2 = A_2\{V_c \cos[\omega_c t + \phi(t)] + V_p \cos\omega_p t\}^2 =$$

$$= \frac{A_2 V_c^2}{2} \cos 2\omega_c t + \cdots \qquad (5)$$

$$A_4 V_{in}^4 = (\frac{A_4}{2} V_c^4 + \frac{3A_4}{2} V_c^2 V_p^2) \cos 2\omega_c t + \cdots \qquad (6)$$

Adding (5) and (6) we get:

$$V_{out}(2\omega_c) = \frac{A_2}{2} V_c^2 (1 + \frac{A_4}{A_2} V_c^2 + \frac{3A_4}{A_2} V_p^2) \qquad (7)$$

Thus, an additional term is added to the amplitude of the pump signal V_p. If A_2 and A_4 have the same sign, the amplitude of the CW signal at $2\omega_c$ will increase with the pump level. Fortunately, as will be seen later, this is indeed the case up to some level of V_p where the small signal approximation collapses.

From the power series in (2), we can also obtain a down converted CW signal at a frequency $\omega_{1,2} = |\omega_p - 2\omega_c|$, by calculating the third order term in the series. The amplitude of this signal will be:

$$V_{out}(\omega_{1,2}) = \frac{3}{2} A_3 V_c^2 V_p \qquad (8)$$

It has to be noted though, that a CW signal of amplitude V_c at the carrier frequency ω_c will generate a second harmonic of the same amplitude as a PN-BPSK signal, therefore, in order to positively identify such a signal, the carrier band has to be monitored simultaneously.

The above theoretical results, which indicate that an improvement in the second harmonic output can be achieved in the presence of a pumping signal were confirmed both by numerical calculations and by laboratory measurements.

NUMERICAL RESULTS

In order to confirm the above theoretical results, a computer simulation of a single-ended mixer was carried out. The model of the mixer consists of a semiconductor diode with an exponential I-V characteristic and a series resistance R_s representing the diode losses. The diode is fed by a 50Ω signal source through a circulator in order to isolate the input from the output. The DC parameters of a detector diode, which was later used in our experiments, were obtained from the measured I-V curve. From this model a transcendental equation for the voltage on the load as a function of time, is obtained. This equation is solved using the Newton-Raphson method. After the time function is calculated, Fourier analysis is applied in order to calculate the various spectral components of interest.

In the case reported here, the power output at the second harmonic $2\omega_c$ and at the down converted frequency $\omega_{1,2} = |2\omega_c - \omega_p|$ was calculated as a function of P_p, the pump power level, with P_c, the carrier power level, as a parameter. The results are shown in Fig 2. It is observed that the outputs at the second harmonic and at the down converted product exhibit a peak at a certain pump power level, decreasing for higher pump levels, leading to the conclusion that the small signal power series model developed in the previous section is not valid anymore at these input levels. At the peak, the second harmonic output is about 34 dB over the non-pumped level in this particular simulation, a significant improvement.

EXPERIMENTAL RESULTS AND CONCLUSIONS

Using the experimental setup shown in Fig 3, measurements of the power output at the second harmonic and at the down converted product $\omega_{1,2}$ were carried on, as a function of the pump power level. These results are shown in Fig 4. These plots show a qualitative similarity to these obtained by computer simulation, alas, numerically they differ. Especially, the boost in second harmonic generation under optimal pump power is now only 18 dB above the non-pumped level. These differences might be attributed to the crudity of our computer model which does not take into account frequency effects; thus, such discrepancies might well be expected at microwave frequencies. However, the experimental results corroborated the computer calculations, at least qualitatively, showing the feasibility of this method for positive identification of PN-BPSK signals, provided that simultaneous monitoring is carried on at the carrier band.

ACKNOWLEDGMENTS

Dr. Zeev Bogan wishes to acknowledge the National Research Council for providing support for his associateship at the Air Force Avionics Laboratory.

APPENDIX B

COMPUTER PROGRAM USAGE

The computer program MIXER is written in FORTRAN IV and intended for interactive use.

Data is entered from the terminal as answers to queries by the program.

1. INPUT

MIXER accomodates the following options according to the specified number of diodes in the circuit, ND:

ND=1 : Single ended mixer.
ND=2 : Limiter or balanced mixer.
ND=4 : Double balanced mixer.

If ND=2 the program asks whether the circuit to be analyzed is a balanced mixer or a limiter. If it is a mixer, the type of hybrid used (90 or 180) has to be specified.

For ND=2 the option exists to specify non-identical diodes in the circuit. This feature is useful to check for effects of unbalance on supposedly balanced configurations.

In case of trouble, it is desirable to obtain the output in the time domain in order to check for nonconvergence of the solutions. This option is available by answering YES to the "TIME DOMAIN ONLY?" query. In this case, the voltages on the diodes and the convergence error at each iteration could be obtained by answering YES to the "INTERMEDIATE ITERATION OUTPUT" query.

For frequency domain simulations the option is between calculation of the one-tone harmonic intermodulation products (SPURS) or the two-tone third-order intermodulation product (IMD). The levels of the

intermodulation products can be calculated as a function of the LO level (PLO) with the signal level (PSIG) as a parameter (1), or as a function of PSIG with PLO as a parameter (2), or as a function of PIN (3), where PIN=PLO=PSIG, for calculation of two-tone sideband levels.

After all the options for the run have been entered, the data is specified next in the following order:

Diode parameters: ALPHA (1/VOLTS), saturation current (IS) (AMPERES), series resistance (RS) (OHMS).

Input and output impedances (ZO and ZL) (OHMS).

LO and RF frequencies (FLO and FSIG) (HZ).

If IMD was specified, enter FSIG2 (second tone frequency).

Power Levels and power steps (dBm):

Option (1): PSIGMIN, PSIGMAX, STEPSIG, PLOMIN, PLOMAX, STEPLO.

Option (2): PLOMIN, PLOMAX, STEPLO, PSIGMIN, PSIGMAX, STEPSIG.

Option (3): PMIN, PMAX, PSTEP.

(Example: Calculate SPURS as a function of PSIG for $-30 \leq$ PSIG ≤ -20 dBm each 2 dB while PLO varies from 0 to 10 dBm in 5 dB steps: PLOMIN, PLOMAX, STEPLO, PSIGMIN, PSIGMAX, STEPSIG = 0, 10, 5, -30, -20, 2.) For time domain only calculations only one set of power levels is specified: PlO, PSIG.

If "SPURS" was specified the number of Spurs desired (NPRODS) is entered next. The order (m,n) of the spurs is entered as follows: m1, n1 m2, n2... m is the coefficient of FLO while n is the coefficient of FSIG. For example, the IF will be given by (1, -1); the LO feedthrough is given by (1,0) and the RF feedthrough is given by (0,1).

For time domain only simulation, the time limit of the calculation TMAX has to be specified in seconds. For frequency domain calculations TMAX is internally calculated.

Next, the integration step DELTAT is entered (seconds).

The maximum number of iterations and the maximum allowed convergence error are entered last.

2. INPUT CONSIDERATIONS

a. Choice of Frequencies

As explained in the text, the choice of the set (FLO, FSIG) does not affect the actual performance of the mixer but will affect the results of the simulation if not carefully chosen. The sampling windown TMAX is internally calculated as: TMAX = 1/|FLO-FSIG| for spur calculations. In order to avoid erroneous results 1/TMAX has to be a common divisor of FLO, FSIG and all their byproducts. A reasonable choice for the set (FLO, FSIG) would be (20, 19) so that TMAX=1. This set also assures that there will be no overlapping of low-order intermodulation products.

For two-tone third-order intermodulation calculations, the choice of the set (FLO, FSIG, FSIG2) is more critical yet since there are more intermodulation products to contend with and overlapping should be avoided. TMAX in this case is calculated as 1/|FSIG-FSIG2| and has to be a common divisor of FLO, FSIG, FSIG2 and all their byproducts. Again it is convenient to choose TMAX=1 as before. We have found that the set (30, 12, 11) works reasonably well.

b. Time Increment DELTAT

According to the Sampling theorem, the sampling rate has to be at least twice the maximum frequency present in the spectrum of the analyzed signal. It was found that for the above frequency choices, DELTAT=10^{-3}s for spur calculations and DELTAT=10^{-4}s for two-tone third-order IMD calculations give accurate results. It is advisable to check doubtful results by running the program again with the same data and a reduced DELTAT.

c. Number of Iterations and Maximum Error

Generally the solutions converge in less than five iterations with an error of less than 10^{-7}. It is advisable to specify the number of iterations as 10 or greater and the maximum allowable error as 10^{-7} or less.

3. OUTPUT

The frequency domain output (spur levels) is filed under TAPE1 while the time domain output is filed under TAPE2.

Up to six IMD products can be accomodated on an iteractive terminal. If the number of spurs (NPRODS) is greater than six, the output has to be diverted to a line printer. Up to 10 spurs can be requested.

4. CONTROL

Mixer uses the matrix inversion subroutine LINV1F which is part of the IMSL library. To attach this library the following command is used: ATTACH, IMSL, ID=X654321, SN=AFIT.

To run the program: XEQ, LDSET, LIB=IMSL, LOAD-LFN where LFN is the file name under which the object deck of MIXER is filed. If immediate output on the terminal is desired use: DISCONT, TAPE1 (or TAPE2) before the XEQ command.

5. EXAMPLES

In the following pages various examples of the use of this program are presented.

EXAMPLE 1

CALCULATION OF TWO-TONE THIRD-ORDER IMD LEVELS

IN A SINGLE-ENDED MIXER

(a) Input

```
*** NON-LINEAR CIRCUIT SIMULATION ***

ENTER OPTIONS FOR THIS RUN:
ENTER NUMBER OF DIODES FOR SIMULATED CIRCUIT.
(TYPE 1,2, OR 4)  ND=1

TIME DOMAIN ONLY? (YES OR NO): NO

CALCULATE SPURS OR 2-TONE 3RD ORDER IMD?
 TYPE SPURS OR IMD:  IMD

DETERMINE WHAT KIND OF CALCULATION DESIRED.
(1)POUT=F(PLO). (2)POUT=F(PSIG). (3)POUT=F(PIN),PIN=PLO=PSIG.
TYPE 1 ,2 OR 3.: 1

ENTER RUN DATA:
ENTER DIODE #1: ALPHA,IS,RS=  40.,1.E-12,10.

ENTER INPUT AND OUTPUT IMPEDANCES ZO,ZL=  50.,50.

ENTER FREQUENCIES FLO,FSIG (HZ):  30.,11.

ENTER 2ND TONE FREQUENCY FSIG2: 12.

ENTER POWER LEVELS (IN DBM):
PSIGMIN,PSIGMAX,STEPSIG,PLOMIN,PLOMAX,STEPLO: -20,-10,10,3,9,3

ENTER SAMPLING INTERVAL DELTAT (SECS): 1.E-4

MAX, NUMBER OF ITERATIONS, MAX. ALLOWED ERROR=10,1.E-7

*** END OF DATA INPUT,BEGIN EXECUTION. ***
*** FIND FREQUENCY DOMAIN OUTPUT ON TAPE1. ***
*** FIND TIME DOMAIN OUTPUT ON TAPE2. ***
```

EXAMPLE 1

(b) Output

```
SIMULATION OF A SINGLE ENDED MIXER
*CALCULATE THE POWER OUTPUT OF 2-TONE 3RD ORDER IMD PRODUCTS
 AS A FUNCTION OF  PLO

DIODE#1: ALPHA= 40.00   IS= 1.00E-12   RS=  10.00
FREQUENCIES: FLO= 3.00E+01  FSIG= 1.10E+01  FSIG2= 1.20E+01 HZ
SOURCE IMPEDANCE= 50.00             LOAD IMPEDANCE= 50.00
RUN PARAMETERS: DELTAT= 1.00E-04    NITER=10        ERMAX= 1.0E-07

**********************************************************************

    PSIG= -20.00 DBM
*     PLO  *     IMD  *    IF   *
*    3.00  *  -84.19  *  -28.27 *
*    6.00  *  -92.93  *  -26.86 *
*    9.00  * -100.24  *  -26.22 *

**********************************************************************

    PSIG= -10.00 DBM
*     PLO  *     IMD  *    IF   *
*    3.00  *  -53.14  *  -18.69 *
*    6.00  *  -62.61  *  -16.98 *
*    9.00  *  -70.14  *  -16.27 *

**********************************************************************
```

EXAMPLE 2

CALCULATION OF SIDEBAND GENERATION

IN A SINGLE-ENDED MIXER

(a) Input

```
*** NON-LINEAR CIRCUIT SIMULATION ***

 ENTER OPTIONS FOR THIS RUN:
 ENTER NUMBER OF DIODES FOR SIMULATED CIRCUIT.
 (TYPE 1,2, OR 4)  ND=1

 TIME DOMAIN ONLY? (YES OR NO): NO

 CALCULATE SPURS OR 2-TONE 3RD ORDER IMD?
  TYPE SPURS OR IMD:  SPURS

 DETERMINE WHAT KIND OF CALCULATION DESIRED.
 (1)POUT=F(PLO). (2)POUT=F(PSIG). (3)POUT=F(PIN),PIN=PLO=PSIG.
 TYPE 1 ,2 OR 3.: 3

 ENTER RUN DATA:
 ENTER DIODE #1: ALPHA,IS,RS=  40.,1.E-12,10.

 ENTER INPUT AND OUTPUT IMPEDANCES ZO,ZL=  50.,50.

 ENTER FREQUENCIES FLO,FSIG (HZ):  20.,19

 ENTER POWER LEVELS (IN DBM):
 PMIN,PMAX,PSTEP=-30,0,3

 ENTER NUMBER OF SPURS DESIRED. (1 TO 10): 4

 ENTER SPUR ORDER M,N. (M*FLO+N*FSIG): 1,-2 2,-3 3,-4 4,-5

 ENTER SAMPLING INTERVAL DELTAT (SECS): 1.E-3

 MAX, NUMBER OF ITERATIONS, MAX. ALLOWED ERROR=10,1.E-7

 *** END OF DATA INPUT,BEGIN EXECUTION. ***
 *** FIND FREQUENCY DOMAIN OUTPUT ON TAPE1. ***
 *** FIND TIME DOMAIN OUTPUT ON TAPE2. ***
```

EXAMPLE 2

(b) Output

```
SIMULATION OF A SINGLE ENDED MIXER
*CALCULATE THE POWER OUTPUT OF SPURIOUS PRODUCTS
 AS A FUNCTION OF PIN.PIN=PSIG=PLO.

DIODE#1: ALPHA= 40.00   IS= 1.00E-12   RS=  10.00
FREQUENCIES: FLO= 2.00E+01  FSIG= 1.90E+01  FSIG2= 0.      HZ
SOURCE IMPEDANCE= 50.00             LOAD IMPEDANCE= 50.00
SPURIOUS:( 1,-2)( 2,-3)( 3,-4)( 4,-5)
RUN PARAMETERS: DELTAT= 1.00E-03   NITER=10      ERMAX= 1.0E-07

*************************************************************************

PIN=PLO=PSIG
```

PIN	(1,-2)	(2,-3)	(3,-4)	(4,-5)
-30.00	-218.75	-250.68	-281.83	-277.74
-27.00	-208.63	-234.80	-266.44	-275.09
-24.00	-197.47	-218.22	-244.41	-281.21
-21.00	-184.36	-200.20	-221.04	-246.47
-18.00	-167.85	-179.47	-195.44	-215.04
-15.00	-145.74	-154.02	-165.83	-180.72
-12.00	-114.97	-120.79	-129.28	-140.25
-9.00	-72.07	-76.32	-82.69	-91.30
-6.00	-37.61	-45.79	-69.54	-63.08
-3.00	-25.72	-53.35	-45.08	-58.07
0.00	-20.48	-34.58	-54.56	-45.70

```
*************************************************************************
```

EXAMPLE 3

CALCULATION OF ONE-TONE IMD LEVELS IN A 90°-HYBRID

BALANCED MIXER AS A FUNCTION OF PLO

(a) Input

```
*** NON-LINEAR CIRCUIT SIMULATION ***

 ENTER OPTIONS FOR THIS RUN:
 ENTER NUMBER OF DIODES FOR SIMULATED CIRCUIT.
 (TYPE 1,2, OR 4)  ND=2

 MIXER OR LIMITER? (TYPE M OR L):  M

 90 OR 180 DEGREE HYBRID? TYPE 90 OR 180: 90

 IDENTICAL DIODES? (YES OR NO):  YES

 TIME DOMAIN ONLY? (YES OR NO): NO

 CALCULATE SPURS OR 2-TONE 3RD ORDER IMD?
  TYPE SPURS OR IMD:  SPURS

 DETERMINE WHAT KIND OF CALCULATION DESIRED.
 (1)POUT=F(PLO). (2)POUT=F(PSIG). (3)POUT=F(PIN),PIN=PLO=PSIG.
 TYPE 1 ,2 OR 3.: 1

 ENTER RUN DATA:
 ENTER DIODE #1: ALPHA,IS,RS=  40.,1.E-12,10.

 ENTER INPUT AND OUTPUT IMPEDANCES ZO,ZL=  50.,50.

 ENTER FREQUENCIES FLO,FSIG (HZ):  20.,19

 ENTER POWER LEVELS (IN DBM):
 PSIGMIN,PSIGMAX,STEPSIG,PLOMIN,PLOMAX,STEPLO: -30,-20,10,5,13,1

 ENTER NUMBER OF SPURS DESIRED. (1 TO 10): 6

 ENTER SPUR ORDER M,N. (M*FLO+N*FSIG): 1,-1 1,-2 2,-1 2,-2 2,-3 3,-2

 ENTER SAMPLING INTERVAL DELTAT (SECS): 1.E-3

 MAX, NUMBER OF ITERATIONS, MAX. ALLOWED ERROR=10,1.E-7

 *** END OF DATA INPUT,BEGIN EXECUTION. ***
 *** FIND FREQUENCY DOMAIN OUTPUT ON TAPE1. ***
 *** FIND TIME DOMAIN OUTPUT ON TAPE2  ***
```

EXAMPLE 3

(b) Output

SIMULATION OF A BALANCED MIXER WITH A 90. DEGREE HYBRID AND IDENTICAL DIODES

*CALCULATE THE POWER OUTPUT OF SPURIOUS PRODUCTS AS A FUNCTION OF PLO

```
DIODE#1: ALPHA= 40.00    IS= 1.00E-12    RS=  10.00
FREQUENCIES: FLO= 2.00E+01  FSIG= 1.90E+01  FSIG2= 0.        HZ
SOURCE IMPEDANCE= 50.00            LOAD IMPEDANCE= 50.00
SPURIOUS:( 1,-1)( 1,-2)( 2,-1)( 2,-2)( 2,-3)( 3,-2)
RUN PARAMETERS: DELTAT= 1.00E-03    NITER=10       ERMAX= 1.0E-07
```

PSIG= -30.00 DBM

PLO	(1,-1)	(1,-2)	(2,-1)	(2,-2)	(2,-3)	(3,-2)
5.00	-41.24	-91.82	-48.56	-96.79	-139.51	-96.24
6.00	-40.62	-97.74	-49.32	-93.83	-131.53	-101.16
7.00	-40.24	-105.40	-50.60	-92.98	-143.00	-106.25
8.00	-40.00	-119.18	-52.34	-93.04	-141.11	-108.96
9.00	-39.85	-111.02	-54.56	-93.27	-128.60	-110.11
10.00	-39.76	-105.61	-57.42	-94.30	-126.21	-113.95
11.00	-39.71	-100.87	-61.43	-95.10	-126.14	-112.83
12.00	-39.69	-103.64	-67.96	-96.84	-146.27	-108.98
13.00	-39.69	-99.33	-89.58	-97.47	-140.91	-110.47

PSIG= -20.00 DBM

PLO	(1,-1)	(1,-2)	(2,-1)	(2,-2)	(2,-3)	(3,-2)
5.00	-31.25	-71.77	-38.59	-76.88	-113.75	-76.26
6.00	-30.63	-77.70	-39.34	-73.87	-108.55	-81.13
7.00	-30.24	-85.72	-40.62	-73.01	-127.74	-86.00
8.00	-30.00	-103.01	-42.35	-73.07	-113.70	-89.31
9.00	-29.85	-91.55	-44.56	-73.50	-104.31	-91.02
10.00	-29.76	-86.04	-47.43	-74.34	-97.69	-93.08
11.00	-29.71	-81.60	-51.43	-75.30	-99.12	-92.07
12.00	-29.69	-83.75	-58.04	-76.51	-121.20	-91.12
13.00	-29.69	-79.88	-81.03	-77.51	-120.39	-90.51

EXAMPLE 4

CALCULATION OF ONE-TONE IMD LEVELS IN A 180°-HYBRID

BALANCED MIXER AS A FUNCTION OF PSIG

(a) Input

```
*** NON-LINEAR CIRCUIT SIMULATION ***

ENTER OPTIONS FOR THIS RUN:
ENTER NUMBER OF DIODES FOR SIMULATED CIRCUIT.
(TYPE 1,2, OR 4)  ND=2

MIXER OR LIMITER? (TYPE M OR L):  M

90 OR 180 DEGREE HYBRID? TYPE 90 OR 180: 180

IDENTICAL DIODES? (YES OR NO):  YES

TIME DOMAIN ONLY? (YES OR NO): NO

CALCULATE SPURS OR 2-TONE 3RD ORDER IMD?
 TYPE SPURS OR IMD:  SPURS

DETERMINE WHAT KIND OF CALCULATION DESIRED.
(1)POUT=F(PLO). (2)POUT=F(PSIG). (3)POUT=F(PIN),PIN=PLO=PSIG.
TYPE 1 ,2 OR 3.: 2

ENTER RUN DATA:
ENTER DIODE #1: ALPHA,IS,RS=  40.,1.E-12,10.

ENTER INPUT AND OUTPUT IMPEDANCES ZO,ZL=  50.,50.

ENTER FREQUENCIES FLO,FSIG (HZ):  20.,19.

ENTER POWER LEVELS (IN DBM):
PLOMIN,PLOMAX,STEPLO,PSIGMIN,PSIGMAX,STEPSIG: 5,10,5,-30,-20,2

ENTER NUMBER OF SPURS DESIRED. (1 TO 10): 6

ENTER SPUR ORDER M,N. (M*FLO+N*FSIG): 1,-1 1,-2 2,-1 2,-2 2,-3 3,-2

ENTER SAMPLING INTERVAL DELTAT (SECS): 1.E-3

MAX, NUMBER OF ITERATIONS, MAX. ALLOWED ERROR=10,1.E-7

*** END OF DATA INPUT,BEGIN EXECUTION. ***
*** FIND FREQUENCY DOMAIN OUTPUT ON TAPE1. ***
*** FIND TIME DOMAIN OUTPUT ON TAPE2. ***
```

EXAMPLE 4

(b) Output

```
SIMULATION OF A BALANCED MIXER WITH A180. DEGREE HYBRID AND
IDENTICAL DIODES

*CALCULATE THE POWER OUTPUT OF SPURIOUS PRODUCTS
 AS A FUNCTION OF PSIG

DIODE#1: ALPHA= 40.00    IS= 1.00E-12    RS=  10.00
FREQUENCIES: FLO= 2.00E+01  FSIG= 1.90E+01  FSIG2= 0.          HZ
SOURCE IMPEDANCE= 50.00            LOAD IMPEDANCE= 50.00
SPURIOUS:( 1,-1)( 1,-2)( 2,-1)( 2,-2)( 2,-3)( 3,-2)
RUN PARAMETERS: DELTAT= 1.00E-03   NITER=10        ERMAX= 1.0E-07

***********************************************************************

   PLO=    5.00 DBM
*   PSIG   * ( 1,-1) * ( 1,-2) * ( 2,-1) * ( 2,-2) * ( 2,-3) * ( 3,-2) *
* -30.00   *  -43.54 * -280.09 *   -47.89 * -281.68 * -128.52 * -281.57 *
* -28.00   *  -41.53 * -277.56 *   -45.90 * -278.85 * -122.52 * -279.85 *
* -26.00   *  -39.53 * -275.30 *   -43.90 * -276.83 * -116.40 * -278.43 *
* -24.00   *  -37.53 * -273.82 *   -41.90 * -275.08 * -110.40 * -276.70 *
* -22.00   *  -35.53 * -271.88 *   -39.91 * -272.97 * -104.46 * -276.30 *
* -20.00   *  -33.52 * -269.81 *   -37.92 * -270.94 *  -98.52 * -275.17 *

***********************************************************************

   PLO=   10.00 DBM
*   PSIG   * ( 1,-1) * ( 1,-2) * ( 2,-1) * ( 2,-2) * ( 2,-3) * ( 3,-2) *
* -30.00   *  -41.72 * -279.20 *   -50.96 * -268.07 * -153.13 * -273.05 *
* -28.00   *  -39.72 * -283.54 *   -48.96 * -266.12 * -146.52 * -270.51 *
* -26.00   *  -37.72 * -277.68 *   -46.96 * -263.85 * -137.70 * -267.93 *
* -24.00   *  -35.72 * -271.37 *   -44.96 * -261.94 * -132.71 * -266.27 *
* -22.00   *  -33.72 * -270.83 *   -42.96 * -260.66 * -126.02 * -264.97 *
* -20.00   *  -31.72 * -272.43 *   -40.96 * -258.84 * -118.71 * -262.84 *

***********************************************************************
```

EXAMPLE 5

CALCULATION OF THE OUTPUT LEVELS OF A LIMITER FED BY TWO SIGNALS

(a) Input

```
*** NON-LINEAR CIRCUIT SIMULATION ***

 ENTER OPTIONS FOR THIS RUN:
 ENTER NUMBER OF DIODES FOR SIMULATED CIRCUIT.
 (TYPE 1,2, OR 4)  ND=2

 MIXER OR LIMITER? (TYPE M OR L): L

 IDENTICAL DIODES? (YES OR NO): YES

 TIME DOMAIN ONLY? (YES OR NO): NO

 CALCULATE SPURS OR 2-TONE 3RD ORDER IMD?
  TYPE SPURS OR IMD: SPURS

 DETERMINE WHAT KIND OF CALCULATION DESIRED.
 (1)POUT=F(PLO). (2)POUT=F(PSIG). (3)POUT=F(PIN),PIN=PLO=PSIG.
 TYPE 1 ,2 OR 3.: 1

 ENTER RUN DATA:
 ENTER DIODE #1: ALPHA,IS,RS=  40.,1.E-12,10.

 ENTER INPUT AND OUTPUT IMPEDANCES ZO,ZL=  50.,50.

 ENTER FREQUENCIES FLO,FSIG (HZ):  20.,19.

 ENTER POWER LEVELS (IN DBM):
 PSIGMIN,PSIGMAX,STEPSIG,PLOMIN,PLOMAX,STEPLO: 5,15,10,0,20,2

 ENTER NUMBER OF SPURS DESIRED. (1 TO 10): 2

 ENTER SPUR ORDER M,N. (M*FLO+N*FSIG): 1,0,0,1

 ENTER SAMPLING INTERVAL DELTAT (SECS): 1.E-3

 MAX, NUMBER OF ITERATIONS, MAX. ALLOWED ERROR=10,1.E-7

 *** END OF DATA INPUT,BEGIN EXECUTION. ***
 *** FIND FREQUENCY DOMAIN OUTPUT ON TAPE1. ***
 *** FIND TIME DOMAIN OUTPUT ON TAPE2. ***
```

EXAMPLE 5

(b) Output

```
SIMULATION OF A LIMITER WITH
IDENTICAL DIODES

*CALCULATE THE POWER OUTPUT OF SPURIOUS PRODUCTS
 AS A FUNCTION OF  PLO

DIODE#1: ALPHA= 40.00    IS= 1.00E-12    RS=  10.00
FREQUENCIES: FLO= 2.00E+01  FSIG= 1.90E+01  FSIG2= 0.       HZ
SOURCE IMPEDANCE= 50.00         LOAD IMPEDANCE= 50.00
SPURIOUS:( 1, 0)( 0, 1)
RUN PARAMETERS: DELTAT= 1.00E-03    NITER=10      ERMAX= 1.0E-07

*************************************************************************

    PSIG=    5.00 DBM
*     PLO   * ( 1, 0) * ( 0, 1) *
*    0.00   *   -1.52 *    4.07 *
*    2.00   *     .33 *    3.75 *
*    4.00   *    2.13 *    3.30 *
*    6.00   *    3.87 *    2.66 *
*    8.00   *    5.55 *    1.77 *
*   10.00   *    7.11 *     .60 *
*   12.00   *    8.44 *    -.57 *
*   14.00   *    9.63 *   -1.49 *
*   16.00   *   10.79 *   -2.25 *
*   18.00   *   11.99 *   -2.88 *
*   20.00   *   13.26 *   -3.40 *

*************************************************************************

    PSIG=   15.00 DBM
*     PLO   * ( 1, 0) * ( 0, 1) *
*    0.00   *   -6.92 *   10.29 *
*    2.00   *   -4.91 *   10.27 *
*    4.00   *   -2.89 *   10.23 *
*    6.00   *    -.88 *   10.17 *
*    8.00   *    1.16 *   10.07 *
*   10.00   *    3.23 *    9.90 *
*   12.00   *    5.35 *    9.60 *
*   14.00   *    7.56 *    9.02 *
*   16.00   *    9.65 *    8.19 *
*   18.00   *   11.46 *    7.31 *
*   20.00   *   12.99 *    6.68 *

*************************************************************************
```

EXAMPLE 6

SIMULATION OF A DOUBLE BALANCED MIXER

WITH INTERMEDIATE ITERATION OUTPUT

(a) Input

```
*** NON-LINEAR CIRCUIT SIMULATION ***

 ENTER OPTIONS FOR THIS RUN:
 ENTER NUMBER OF DIODES FOR SIMULATED CIRCUIT.
 (TYPE 1,2, OR 4)  ND=4

 IDENTICAL DIODES? (YES OR NO):  YES

 TIME DOMAIN ONLY? (YES OR NO): YES

 PRINTOUT OPTIONS:
 INTERMEDIATE ITERATION OUTPUT? (YES OR NO): YES

 ENTER RUN DATA:
 ENTER DIODE #1: ALPHA,IS,RS=  40.,1.E-12,10.

 ENTER INPUT AND OUTPUT IMPEDANCES ZO,ZL=  50.,50.

 ENTER FREQUENCIES FLO,FSIG (HZ):  20.,19.

 ENTER POWER LEVELS (IN DBM):
 PLO,PSIG=  10,-10

 ENTER SAMPLING WINDOW TMAX (SECS)=  1.E-2

 ENTER SAMPLING INTERVAL DELTAT (SECS): 2.E-3

 MAX, NUMBER OF ITERATIONS, MAX. ALLOWED ERROR=10,1.E-7

 *** END OF DATA INPUT,BEGIN EXECUTION. ***
 *** FIND FREQUENCY DOMAIN OUTPUT ON TAPE1. ***
 *** FIND TIME DOMAIN OUTPUT ON TAPE2. ***
```

EXAMPLE 6

(b) Output

```
SIMULATION OF A DOUBLE BALANCED MIXER WITH
IDENTICAL DIODES

DIODE#1: ALPHA= 40.00    IS= 1.00E-12   RS=  10.00
FREQUENCIES: FLO= 2.00E+01  FSIG= 1.90E+01  FSIG2= 0.       HZ
SOURCE IMPEDANCE= 50.00             LOAD IMPEDANCE= 50.00
RUN PARAMETERS: DELTAT= 2.00E-03   NITER=10       ERMAX= 1.0E-07

*************************************************************************

          PSIG= -10.00 DBM      PLO=  10.00 DBM
   T        VD(1)      VD(2)      VD(3)      VD(4)      ERROR      ITER IDT
0.         0.         0.         0.         0.         0.            1  1
0.         0.         0.         0.         0.         0.            2  1


2.000E-03 2.250E-01 2.723E-01-2.250E-01-2.723E-01 2.496E-01    1  1
2.000E-03 2.250E-01 2.723E-01-2.250E-01-2.723E-01 5.560E-11    2  1


4.000E-03 4.358E-01 5.277E-01-4.358E-01-5.277E-01 2.192E-01    1  1
4.000E-03 4.470E-01 5.066E-01-4.213E-01-5.351E-01 8.338E-04    2  1
4.000E-03 4.536E-01 4.952E-01-4.136E-01-5.395E-01 2.495E-04    3  1
4.000E-03 4.547E-01 4.932E-01-4.122E-01-5.402E-01 8.003E-06    4  1
4.000E-03 4.547E-01 4.931E-01-4.121E-01-5.402E-01 4.903E-09    5  1


6.000E-03 6.765E-01 5.981E-01-5.143E-01-7.873E-01 1.317E-01    1  1
6.000E-03 6.516E-01 5.758E-01-4.983E-01-7.696E-01 1.695E-03    2  1
6.000E-03 6.268E-01 5.586E-01-4.859E-01-7.520E-01 1.367E-03    3  1
6.000E-03 6.027E-01 5.512E-01-4.803E-01-7.351E-01 9.567E-04    4  1
6.000E-03 5.802E-01 5.516E-01-4.801E-01-7.195E-01 7.500E-04    5  1
6.000E-03 5.620E-01 5.528E-01-4.806E-01-7.068E-01 4.931E-04    6  1
6.000E-03 5.517E-01 5.535E-01-4.809E-01-6.997E-01 1.552E-04    7  1
6.000E-03 5.492E-01 5.536E-01-4.809E-01-6.980E-01 9.220E-06    8  1
6.000E-03 5.491E-01 5.536E-01-4.809E-01-6.979E-01 2.096E-08    9  1


8.000E-03 5.762E-01 5.774E-01-5.168E-01-7.896E-01 1.099E-02    1  1
8.000E-03 5.693E-01 5.716E-01-5.127E-01-7.847E-01 1.215E-04    2  1
8.000E-03 5.682E-01 5.709E-01-5.122E-01-7.839E-01 2.435E-06    3  1
8.000E-03 5.682E-01 5.709E-01-5.122E-01-7.839E-01 8.219E-10    4  1


*************************************************************************
```

6. PROGRAM LISTING

The comments on the enclosed listing make the program MIXER self explanatory. The equivalence between various symbols in the program and in the test follows:

PROGRAM	TEXT
AJ	J
AJINV	J^{-1}
FV	F
VD	v
ID	i
CVD	A
CE	Z
CVIN	B

```
      PROGRAM MIXER(INPUT,OUTPUT,TAPE1,TAPE2)
C  *******************************************************************
C  * THIS PROGRAM CALCULATES THE PERFORMANCE OF NON-LINEAR CIRCUITS  *
C  * CONTAINING SEMICONDUCTOR DIODES. (SINGLE ENDED,BALANCED,         *
C  * AND DOUBLE BALANCED MIXERS, AND BACK TO BACK DIODE LIMITERS).   *
C  * THE VARIOUS OPTIONS ARE:                                        *
C  *   IDENTICAL OR NON-IDENTICAL DIODES.                            *
C  *   SOLUTION IN THE TIME DOMAIN ONLY.                             *
C  *   CALCULATION OF ONE TONE IMD'S OR TWO TONE THIRD ORDER IMD.    *
C  *   ONE OF THE FOLLOWING POWER COMBINATIONS:                      *
C  *    A)CONSTANT SIGNAL POWER; POUT AS A FUNCTION OF LO POWER.     *
C  *    B) CONSTANT LO POWER; POUT AS A FUNCTION OF SIGNAL POWER.    *
C  *    C) SIGNAL POWER=LO POWER.                                    *
C  *******************************************************************
C
      IMPLICIT LOGICAL(L)
      REAL IS(4),ALPHA(4),RS(4),E(4),E1(4),EP(4),VD(4),ID(4)
      DIMENSION AJ(4,4),AJINV(4,4),WK(4),MPROD(10),NPROD(10),OMEG(10),
     1POUT(10),VSIN(10),VCOS(10),CVD(4,4),CE(4,4),CVIN(4,4),
     1VIN(4),VFINAL(4),FV(4)
      COMMON/Z/ZO
      PRINT 1
      LSAME=LTDOM=LTHIRD=LITER=LIMIT=.FALSE.
C
C  *******************************************************************
C  *     BEGIN OPTIONS INPUT                                         *
C  *******************************************************************
      PRINT*,' ENTER OPTIONS FOR THIS RUN:'
      PRINT*,' ENTER NUMBER OF DIODES FOR SIMULATED CIRCUIT.'
      PRINT*,' (TYPE 1,2, OR 4)  ND='
      READ*,ND
      IF(ND.EQ.4)GO TO 90
      LSAME=ND.EQ.1
      IF(ND.EQ.1)GO TO 95
      PRINT*,' MIXER OR LIMITER? (TYPE M OR L):  '
      READ 2,ANS
      LIMIT=ANS.EQ.1HL
      IF(.NOT.LIMIT)PRINT*,' 90 OR 180 DEGREE HYBRID? TYPE 90 OR 180:'
      IF(.NOT.LIMIT)READ*,DEG
   90 PRINT*,' IDENTICAL DIODES? (YES OR NO):  '
      READ 2,ANS
      LSAME=ANS.EQ.1HY
   95 PRINT*,' TIME DOMAIN ONLY? (YES OR NO): '
      READ 2,ANS
      LTDOM=ANS.EQ.1HY
      IF(LTDOM)GO TO 100
      PRINT*,' CALCULATE SPURS OR 2-TONE 3RD ORDER IMD? '
      PRINT*,'  TYPE SPURS OR IMD:  '
      READ 2,ANS
      LTHIRD=ANS.EQ.1HI
      PRINT*,' DETERMINE WHAT KIND OF CALCULATION DESIRED.'
```

```
      PRINT*,' (1)POUT=F(PLO). (2)POUT=F(PSIG).',
     1' (3)POUT=F(PIN),PIN=PLO=PSIG.'
      PRINT*,' TYPE 1 ,2 OR 3.:'
      READ*,IFLAG
      GO TO 110
  100 PRINT*,' PRINTOUT OPTIONS: '
      PRINT*,' INTERMEDIATE ITERATION OUTPUT? (YES OR NO): '
      READ 2,ANS
      LITER=ANS.EQ.1HY
      IFLAG=1
C
C     ****************************************************************
C     *              BEGIN DATA INPUT                                *
C     ****************************************************************
  110 PRINT*,' ENTER RUN DATA:'
      ND1=ND
      IF(LSAME)ND1=1
      DO 115 I=1,ND1
      PRINT*,' ENTER DIODE #',I,': ALPHA,IS,RS= '
  115 READ*,ALPHA(I),IS(I),RS(I)
      IF(.NOT.LSAME)GO TO 140
      DO 120 I=2,4
      ALPHA(I)=ALPHA(1)
      IS(I)=IS(1)
  120 RS(I)=RS(1)
  140 PRINT*,' ENTER INPUT AND OUTPUT IMPEDANCES ZO,ZL= '
      READ*,ZO,ZL
      PRINT*,' ENTER FREQUENCIES FLO,FSIG (HZ): '
      READ*,FLO,FSIG
      IF(LTHIRD)PRINT*,' ENTER 2ND TONE FREQUENCY FSIG2: '
      IF(LTHIRD)READ*,FSIG2
      PRINT*,' ENTER POWER LEVELS (IN DBM):'
      IF(LTDOM)GO TO 152
      IF(IFLAG.EQ.3)GO TO 144
      IF(IFLAG.EQ.1)PRINT*,
     1' PSIGMIN,PSIGMAX,STEPSIG,PLOMIN,PLOMAX,STEPLO:'
      IF(IFLAG.EQ.2)PRINT*,
     1' PLOMIN,PLOMAX,STEPLO,PSIGMIN,PSIGMAX,STEPSIG:'
      READ*,PCMIN,PCMAX,PCSTEP,PMIN,PMAX,PSTEP
      GO TO 148
  144 PRINT*,' PMIN,PMAX,PSTEP= '
      READ*,PMIN,PMAX,PSTEP
C
  148 IF(LTHIRD)GO TO 156
      PRINT*,' ENTER NUMBER OF SPURS DESIRED. (1 TO 10): '
      READ*,NPRODS
      PRINT*,' ENTER SPUR ORDER M,N. (M*FLO+N*FSIG): '
      READ*,(MPROD(I),NPROD(I),I=1,NPRODS)
      GO TO 156
  152 PRINT*,' PLO,PSIG= '
```

```
      READ*,PMIN,PCMIN
      PCMAX=PCMIN
      PMAX=PMIN
      PCSTEP=PSTEP=0.
      PRINT*,' ENTER SAMPLING WINDOW TMAX (SECS)=  '
      READ*,TMAX
  156 PRINT*,' ENTER SAMPLING INTERVAL DELTAT (SECS): '
      READ*,DELTAT
      PRINT*,' MAX, NUMBER OF ITERATIONS, MAX. ALLOWED ERROR=  '
      READ*,NITER,ERMAX
      PRINT*,' *** END OF DATA INPUT,BEGIN EXECUTION. ***'
      PRINT*,' *** FIND FREQUENCY DOMAIN OUTPUT ON TAPE1. ***'
      PRINT*,' *** FIND TIME DOMAIN OUTPUT ON TAPE2. ***'
C
C ***********************************************************************
C *     BEGIN TITLE PRINTOUT                                            *
C ***********************************************************************
      ITAPE=1
      IF(LTDOM)ITAPE=2
      IF(ND.EQ.1)WRITE(ITAPE,8)
      IF(ND.EQ.4)WRITE(ITAPE,10)
      IF(LIMIT)WRITE(ITAPE,12)
      IF(ND.EQ.2.AND..NOT.LIMIT)WRITE(ITAPE,14)DEG
      IF(LSAME.AND.ND.NE.1)WRITE(ITAPE,16)
      IF(.NOT.LSAME)WRITE(ITAPE,18)
      IF(LTDOM)GO TO 168
      IF(IFLAG.EQ.3)GO TO 166
      PV=4H PLO
      IF(IFLAG.EQ.2)PV=4HPSIG
      IF(LTHIRD)GO TO 162
      WRITE(1,24)PV
      GO TO 168
  162 WRITE(1,26)PV
      GO TO 168
  166 WRITE(1,28)
  168 CONTINUE
      DO 170 I=1,ND1
  170 WRITE(ITAPE,30)I,ALPHA(I),IS(I),RS(I)
      WRITE(ITAPE,32)FLO,FSIG,FSIG2
      WRITE(ITAPE,33)ZO,ZL
      IF(.NOT.(LTHIRD.OR.LTDOM))WRITE(1,34)NPRODS,
     1(MPROD(I),NPROD(I),I=1,NPRODS)
      WRITE(ITAPE,36)DELTAT,NITER,ERMAX
C
C ***********************************************************************
C *      BEGIN INITIALIZATION                                           *
C ***********************************************************************
      IF(LTDOM)NPRODS=1
      IF(LTHIRD)NPRODS=2
      PI=ACOS(-1.)
```

```
      RT2=SQRT(2.)
      OMSIG=2*PI*FSIG
      OMLO=2.*PI*FLO
      NP=NPC=1
      IF(PSTEP.NE.0.)NP=1+(PMAX-PMIN)/PSTEP
      IF(PCSTEP.NE.0.)NPC=1+(PCMAX-PCMIN)/PCSTEP
      IF(LTDOM)GO TO 230
      TMAX=1./ABS(FLO-FSIG)
      IF(LTHIRD)GO TO 200
      DO 180 I=1,NPRODS
  180 OMEG(I)=ABS(MPROD(I)*OMLO+NPROD(I)*OMSIG)
      GO TO 220
  200 TMAX=AMAX1(TMAX,1./ABS(FSIG-FSIG2))
      OMSIG2=2.*PI*FSIG2
      OMEG(1)=ABS(2.*OMSIG-OMSIG2-OMLO)
      OMEG(2)=ABS(OMLO-OMSIG)
  220 IF(IFLAG.NE.3)GO TO 230
      APV=4H PIN
      WRITE(1,38)
      IF(.NOT.LTHIRD)WRITE(1,40)APV,NPRODS,(MPROD(I),NPROD(I),
     1I=1,NPRODS)
      IF(LTHIRD)WRITE(1,42)APV
C
C ******************************************************************
C *         INITIALIZE CIRCUIT MATRICES                            *
C ******************************************************************
  230 DO 240 I=1,4
      DO 235 J=1,4
  235 CVD(I,J)=CE(I,J)=CVIN(I,J)=0.
  240 CONTINUE
      IF(ND.EQ.4)GO TO 250
      IF(ND.EQ.2)GO TO 242
C         ***********************
C         * SINGLE ENDED MIXER *
C         ***********************
C
      CVD(1,1)=1.
      CE(1,1)=RS(1)+ZO
      CVIN(1,1)=-1.
      GO TO 260
C
C         ******************
C         * BALANCED MIXER *
C         ******************
  242 CVD(1,1)=CVD(2,2)=1.
      IF(LIMIT)GO TO 245
      CE(1,1)=ZL+ZO+RS(1)
      CE(2,2)=ZL+ZO+RS(2)
      CE(1,2)=CE(2,1)=-ZL
      CVIN(1,1)=-1.
```

```
      CVIN(2,2)=1.
      GO TO 260
C
C          ***********
C          * LIMITER *
C          ***********
  245 DIV=ZL/(ZL+ZO)
      Z1=DIV*ZO
      CE(1,1)=RS(1)+Z1
      CE(2,2)=RS(2)+Z1
      CE(1,2)=CE(2,1)=-Z1
      CVIN(1,1)=-DIV
      CVIN(2,2)=DIV
      GO TO 260
C
C          **************************
C          * DOUBLE BALANCED MIXER *
C          **************************
  250 CVD(1,1)=CVD(1,2)=CVD(2,2)=CVD(2,3)=CVD(3,2)=CVD(4,1)=
     1CVD(4,2)=CVD(4,3)=CVD(4,4)=1.
      CE(1,1)=RS(1)+ZO/2.
      CE(1,2)=CE(2,2)=RS(2)+ZO/2.
      CE(1,3)=CE(1,4)=CE(2,1)=CE(2,4)=-ZO/2.
      CE(2,3)=RS(3)+ZO/2.
      CE(3,1)=CE(3,3)=-(ZO/2.+ZL)
      CE(3,2)=RS(2)+ZO+ZL
      CE(3,4)=ZL
      DO 255 I=1,4
  255 CE(4,I)=RS(I)
      CVIN(1,1)=-1.
      CVIN(2,2)=-1.
      CVIN(3,1)=CVIN(3,2)=-.5
  260 CONTINUE
C
C ***********************************************************************
C *     PARAMETER LOOP                                                  *
C ***********************************************************************
C
      DO 1000 KCSTEP=1,NPC
      PCONST=PCMIN+(KCSTEP-1)*PCSTEP
      VCONST=F(PCONST)
C
C          ************************
C          * VARIABLE POWER LOOP *
C          ************************
C
      DO 900 KSTEP=1,NP
      T=0.
      DO 280 I=1,NPRODS
  280 VCOS(I)=VSIN(I)=0.
```

```
      DO 290 I=1,ND
  290 VIN(I)=VFINAL(I)=VD(I)=0.
      PVAR=PMIN+(KSTEP-1)*PSTEP
      VVAR=F(PVAR)
      IF(IFLAG.EQ.3)GO TO 320
      IF(IFLAG.EQ.2)GO TO 300
      VSIG=VCONST
      VLO=VVAR
      PSIG=PCONST
      PLO=PVAR
      APC=5HPSIG=
      APV=4H PLO
      GO TO 340
  300 VSIG=VVAR
      VLO=VCONST
      PLO=PCONST
      PSIG=PVAR
      APC=5H PLO=
      APV=4HPSIG
      GO TO 340
  320 VSIG=VVAR
      VLO=VSIG
      PSIG=PLO=PVAR
  340 VSIG2=0.
      IF(LTHIRD)VSIG2=VSIG
      IF(LTDOM.OR.(KSTEP.GT.1).OR.(IFLAG.EQ.3))GO TO 345
      WRITE(1,44)APC,PCONST
      IF(.NOT.LTHIRD)WRITE(1,40)
     1APV,NPRODS,(MPROD(I),NPROD(I),I=1,NPRODS)
      IF(LTHIRD)WRITE(1,42)APV
  345 IF(LTDOM)WRITE(2,46)PSIG,PLO
      IF(LTDOM.AND..NOT.LITER)WRITE(2,48)
      ITER=IDT=1
      IF(LITER)WRITE(2,49)
C
C          ******************
C          * TIME STEP LOOP *
C          ******************
  350 CONTINUE
C
C     CALCULATE INPUT VOLTAGES AT T
C
      IF(ND.EQ.4)GO TO 370
      IF(LIMIT.OR.ND.EQ.1)GO TO 360
C
C       BALANCED MIXER
C
      IF(DEG.EQ.180.)GO TO 354
      VIN(1)=RT2/2.*(VLO*SIN(OMLO*T)+VSIG*COS(OMSIG*T)+
     1VSIG2*COS(OMSIG2*T))
```

```
      VIN(2)=RT2/2.*(VLO*COS(OMLO*T)+VSIG*SIN(OMSIG*T)+
     1VSIG2*SIN(OMSIG2*T))
      IF(T.GT.0.)GOTO 380
C
C   INITIAL GUESS AT T=0
C
      VD(1)=VIN(1)
      VD(2)=-VIN(2)
      VMAX=1/ALPHA(1)*ALOG(ABS(VIN(1))/(CE(1,1)*IS(1)))
      IF(VD(1).LT.VMAX)GO TO380
      VD(1)=VMAX
      GO TO 380
  354 VIN1=RT2/2.*VLO*SIN(OMLO*T)
      VIN2=RT2/2.*(VSIG*SIN(OMSIG*T)+VSIG2*SIN(OMSIG2*T))
      VIN(1)=-VIN1+VIN2
      VIN(2)=VIN1+VIN2
      GO TO 380
C
C              LIMITER AND SINGLE ENDED MIXER
C
  360 VIN(1)=VIN(2)=VLO*SIN(OMLO*T)+VSIG*SIN(OMSIG*T)+
     1VSIG2*SIN(OMSIG2*T)
      GO TO 380
C
C       DOUBLE BALANCED MIXER
C
  370 VIN(1)=VLO*SIN(OMLO*T)
      VIN(2)=VSIG*SIN(OMSIG*T)+VSIG2*SIN(OMSIG2*T)
  380 CONTINUE
C
C ***********************************************************************
C *           ITERATION LOOP                                            *
C ***********************************************************************
C
      DO 390 I=1,ND
      E1(I)=0.
      IF(ALPHA(I)*VD(I).GT.100.)GO TO 420
      IF(ALPHA(I)*VD(I).GT.-100.)E1(I)=EXP(ALPHA(I)*VD(I))
      E(I)=IS(I)*(E1(I)-1.)
  390 EP(I)=IS(I)*ALPHA(I)*E1(I)
C
C           CALCULATE FV AND JACOBIAN
C
      DO 400 I=1,ND
      FV(I)=0.
      DO 395 J=1,ND
      FV(I)=FV(I)+CVD(I,J)*VD(J)+CE(I,J)*E(J)+CVIN(I,J)*VIN(J)
  395 AJ(I,J)=CVD(I,J)+CE(I,J)*EP(J)
  400 CONTINUE
C
```

```
C           CALCULATE INVERSE OF JACOBIAN
C
      CALL LINV1F(AJ,ND,4,AJINV,0,WK,IER)
C     THE MATRIX AJ IS SINGULAR WHEN IER=129
      IF(IER.EQ.129)GO TO 440
      ERROR=0.
C
C           CALCULATE DIODE VOLTAGES
C
      DO 410 I=1,ND
      VDN=0.
      DO 405 J=1,ND
  405 VDN=VDN+AJINV(I,J)*FV(J)
      ERROR=ERROR+VDN**2
      VDN=VD(I)-VDN
  410 VD(I)=VDN
      IF(LITER)WRITE(2,60)T,VD,ERROR,ITER,IDT
      IF(ERROR.LT.ERMAX.AND.ITER.GT.1)GO TO 460
      ITER=ITER+1
      IF(ITER.GT.NITER)GO TO 420
      GO TO 380
C
C        IF SOLUTION DOES NOT CONVERGE REDUCE TIME STEP
C
  420 ITER=1
      IF(T.EQ.0.)GO TO 440
      T=TLAST+DELTAT/(2**IDT)
      IF(T.LE.T1)T=T1+DELTAT/(2**(IDT+1))
      DO 430 I=1,ND
  430 VD(I)=VFINAL(I)
      IDT=IDT+1
      IF(IDT.GT.4)GO TO 440
      GO TO 350
  440 WRITE(ITAPE,65)T
      PRINT 65,T
      STOP
  460 IF(LITER)WRITE(2,50)
C
C        CALCULATE DIODE CURRENTS AND LOAD VOLTAGE
C
      DO 480 I=1,ND
      ID(I)=-IS(I)
  480 IF(ALPHA(I)*VD(I).GT.-100.)
     1ID(I)=IS(I)*(EXP(ALPHA(I)*VD(I))-1.)
      VLOAD=(ID(1)-ID(2))*ZL
      IF(ND.EQ.1)VLOAD=ID(1)*RS(1)+VD(1)-VIN(1)/2.
      IF(LIMIT)VLOAD=VD(1)+ID(1)*RS(1)
      IF(ND.EQ.4)VLOAD=ZL*(ID(4)+ID(2)-ID(1)-ID(3))
      IF(LTDOM.AND..NOT.LITER)WRITE(2,60)T,VD,VLOAD,ITER,IDT
      IF(IDT.GT.1)GO TO 520
```

```
      TLAST=T
      IF(LTDOM)GO TO 520
C
C            CALCULATE FOURIER COMPONENTS AND POWER OUTPUT
C
      DO 500 MN=1,NPRODS
      VCOS(MN)=VCOS(MN)+VLOAD*COS(OMEG(MN)*T)
  500 VSIN(MN)=VSIN(MN)+VLOAD*SIN(OMEG(MN)*T)
  520 T1=T
      DO 530 I=1,ND
  530 VFINAL(I)=VD(I)
      T=TLAST+DELTAT
      ITER=IDT=1
      IF(T.LT.TMAX-DELTAT/10.)GO TO 350
      ADT=(2.*DELTAT/TMAX)**2
      DO 560 MN=1,NPRODS
      IF(LTDOM)GO TO 900
      POUT(MN)=10.*ALOG10(ADT*(VCOS(MN)**2+VSIN(MN)**2)/(2.*ZL)*1.E3)
      IF(OMEG(MN).EQ.0.)POUT(MN)=POUT(MN)+3.
  560 CONTINUE
      WRITE(1,70)PVAR,NPRODS,(POUT(MN),MN=1,NPRODS)
  900 CONTINUE
 1000 CONTINUE
      WRITE(ITAPE,72)
      IF(.NOT.LTDOM)WRITE(1,74)
      STOP
C
C  ********************************************************************
C  *    FORMAT STATEMENTS                                             *
C  ********************************************************************
    1 FORMAT(' *** NON-LINEAR CIRCUIT SIMULATION ***',/)
    2 FORMAT(A1)
    8 FORMAT(1H1,5X,'SIMULATION OF A SINGLE ENDED MIXER')
   10 FORMAT(1H1,5X,'SIMULATION OF A DOUBLE BALANCED MIXER WITH')
   12 FORMAT(1H1,5X,'SIMULATION OF A LIMITER WITH')
   14 FORMAT(1H1,5X,'SIMULATION OF A BALANCED MIXER WITH A',F4.0,
     1' DEGREE HYBRID AND')
   16 FORMAT(6X,'IDENTICAL DIODES',/)
   18 FORMAT(6X,'NON-IDENTICAL DIODES',/)
   24 FORMAT(5X,'*CALCULATE THE POWER OUTPUT OF SPURIOUS PRODUCTS',
     1/5X,' AS A FUNCTION OF ',A4,/)
   26 FORMAT(5X,'*CALCULATE THE POWER OUTPUT OF 2-TONE 3RD ORDER',
     1' IMD PRODUCTS',/6X,'AS A FUNCTION OF ',A4,/)
   28 FORMAT(5X,'*CALCULATE THE POWER OUTPUT OF SPURIOUS PRODUCTS',
     1/5X,' AS A FUNCTION OF PIN.PIN=PSIG=PLO.',/)
   30 FORMAT(5X,'DIODE#',I1,': ALPHA=',F6.2,3X,'IS=',1PE9.2,
     13X,'RS=',0PF7.2)
   32 FORMAT(5X,'FREQUENCIES: FLO=',1PE9.2,2X,'FSIG=',1PE9.2,
     12X,'FSIG2=',1PE9.2,' HZ')
   33 FORMAT(5X,'SOURCE IMPEDANCE=',F6.2,10X,'LOAD IMPEDANCE=',
```

```
      1F6.2)
   34 FORMAT(5X,'SPURIOUS:',=('(',I2,',',I2,')'))
   36 FORMAT(5X,'RUN PARAMETERS: DELTAT=',1PE9.2,3X,'NITER=',
     1I2,5X,' ERMAX=',1PE8.1,/)
   38 FORMAT(/,1X,120('*')//5X,'PIN=PLO=PSIG')
   40 FORMAT(' *',3X,A4,2X,'*',=(1X,'(',I2,',',I2,') *'))
   42 FORMAT(' *',3X,A4,2X,'*      IMD  *       IF    *')
   44 FORMAT(/,1X,120('*')//5X,A5,F7.2,' DBM')
   46 FORMAT(/,1X,120('*')//10X,'PSIG=',F7.2,' DBM',
     15X,'PLO=',F7.2,' DBM')
   48 FORMAT(3X,'T',T12,'VD(1)',T22,'VD(2)',T32,'VD(3)',
     1T42,'VD(4)',T52,'VLOAD',T62,'ITER',1X,'IDT')
   49 FORMAT(3X,'T',T12,'VD(1)',T22,'VD(2)',T32,'VD(3)',
     1T42,'VD(4)',T52,'ERROR',T62,'ITER',1X,'IDT')
   50 FORMAT(/)
   60 FORMAT(6(1PE10.3),2X,2I3)
   65 FORMAT(' THE SOLUTION DOES NOT CONVERGE AT T=',1PE15.4)
   70 FORMAT(' *',F7.2,2X,'*',=(1X,F7.2,' *'))
   72 FORMAT(/,1X,120('*'))
   74 FORMAT(1H1)
      END


      FUNCTION F(P)
      COMMON/Z/ZO
      F=10.**(P/20)*SQRT(8.*ZO/1000.)
      RETURN
      END
```

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